REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
					19b. TELEPHONE NUMBER *(Include area code)*

GEORGIA TECH VERTICAL LIFT RESEARCH CENTER OF EXCELLENCE

W911W6-11-2-0010
Final Technical Report

For the period
September 15, 2011 – September 14, 2017

Prepared by

Prof. Daniel P. Schrage
daniel.schrage@aerospace.gatech.edu
Phone: 404-894-6257
School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0150

Submitted to

Dr. Mahendra Bhagwat
Aeroflightdynamics Directorate (AMRDEC)
US Army Research, Development, and Engineering Command
Mail Stop 219-3
Ames Research Center Moffett Field, CA 94035-0001
(650) 604-2893
mahendra.j.bhagwat.civ@mail.mil

and

Hope McClain
US Army Aviation Technology Directorate
Fort Eustis
VA 23604-5577

December 14, 2017

Distribution Statement A: Approved for public release; distribution is unlimited.

SUMMARY

The 2011-2016 Georgia Tech Vertical Lift Research Center of Excellence (VLRCOE) consisted of principal investigators from the Schools of Aerospace and Mechanical Engineering at the Georgia Institute of Technology, as well as co-principal investigators from the University of Michigan, Ohio State University, Purdue University, the University of Texas at Arlington, and Washington University in St. Louis, Missouri. The VLRCOE supported eleven full-term tasks selected at the beginning of the VLRCOE, along with six additional plus-up tasks that typically lasted one-two years. The VLRCOE was supported by a total of $8,305,467.24 in US Government funding, augmented with cost-share funding of $2,282,123 from the participating universities.

The tasks partially or fully supported approximately 65 graduate students, many of whom entered the workforce in rotorcraft positions that were directly a result of this Center's funding. Approximately 30 undergraduate researchers funded by the universities or earning college credit contributed directly and significantly to the VLRCOE tasks.

The quality of the research can be identified via several metrics. Almost 80 papers have already appeared in peer-reviewed journals, and over 130 conference papers have been presented. These publications include a number of best papers, including the Annual Forum of the American Helicopter Society (Makeev (3), Smith (2)). American Society of Mechanical Engineers (Ruzzene), and the American Society of Composites (Makeev). The *Journal of Unmanned Systems* selected one of Dr. Prasad's papers as an annual Best Paper. Of particular mention is Dr. Gregory's joint Army-OSU paper selected as the Gessow Best Paper in 2012, and Dr. Makeev's paper selected as the Cheeseman Best Paper at the European Rotorcraft Forum, which remains to date the only Cheeseman Award presented to an all US-authored paper. Dr. Ruzzene was awarded a patent for his research, and several software disclosures have resulted in licensing or transfer of algorithms to outside groups (Hodges, Menon, Prasad, Ruzzene, Sankar, Smith, Yu).

Another metric is outstanding technical awards where VLRCOE principal investigators were honored and which involved their VLRCOE research. AHS Team Awards included faculty on the Howard Hughes Award (Sankar, 2014) and Agusta-Westland International Fellowship Award (Smith, 2012 and 2014). Two faculty members were part of NASA Group Achievement Awards (Gregory, 2012 and Smith, 2017).

Individual awards also attest to the quality of the faculty and students performing VLRCOE research. During this time period, faculty PI honors included election as AHS Fellow (Prasad, Sankar, Smith), AIAA Fellow (Cesnik, Prasad, Sankar,

Smith), ASME Fellow (Hodges, Yu), RAeS (Cesnik, Mavris), Two faculty were selected to give AHS Nikolsky Lectures (Hodges and Friedman) during the award period.

Notable other technical awards included Prof. Hodges and Prof. Peters' award of the Spirit of St. Louis Medal (ASME). Prof. Hodges also received the Ashley Aeroelasticity Award (AIAA) and SDM Award (AIAA). Prof. Peters was awarded the AIAA Reed Aeronautics medal. Prof. Gregory received the Ralph Teetor Award (SAE).

Georgia Tech had submissions in both the Graduate and Undergraduate AHS Student Design Competition (SDC) every year of the VLRCOE, winning or placing each year. Dr. Johnson's student team won first place in 2015 AHS Autonomous Micro Air Vehicle Competition.

Students working directly on VLRCOE projects also won approximately 14 Vertical Flight Foundation Scholarships, while three students were also Georgia Tech Presidential Fellows. Daniel Prosser was twice named an Achievement Rewards for College Scientists (ARCS) Scholar, and was named as an Aviation Week Twenty-20 Aerospace engineer to watch. Many of the graduate students also performed internships at AFDD, AED, ARL, NASA, and industry.

Technology transition of the basic research within this VLRCOE remains a high priority. Each project task provides a short synopsis of the technology transition to date, as well as significant technical collaborations with top researchers in academia, government and industry.

Technical Project Summaries

SUMMARY OF TECHNICAL AWARDS

In this section, a brief summary of each project task is provided, along with details of the metrics of the project. Each project task summary includes the background, research objectives and technical accomplishments. Metrics include students supported, along with awards, papers, patents/software disclosures and technology transfer efforts.

Task 1.1 (GT-1): Next Generation VABS for More Realistic Modeling of Composite Blades

PIs: Dewey H. Hodges (Georgia Tech), Wenbin Yu (USU – at Purdue since 8/2013)

Background: The efficient, high-fidelity cross-sectional analysis tool, VABS, developed at Georgia Tech, is the only analysis of its kind, providing a variety of engineering models in the form of generalized classical, Timoshenko, and Vlasov models, along with various non-classical effects important for composite rotor blades made with arbitrary geometry and materials. The theory behind VABS rigorously decouples the complex 3D blade analysis into a 2D sectional analysis and a 1D beam analysis. Relative to 3D analyses, two to three orders of magnitude in computing time can be saved using VABS with little loss of accuracy. In the previous cycle, the main accomplishments were studies involving span-wise non-uniformity and extensive validation and verification of various features such as initial twist and curvature and composite sections. Further to this, multi-physics beam models were developed for smart blades design and analysis. These models are implemented in VABS and are extensively validated using results in the literature and 3D analysis. The most recent version of VABS can model fully coupled thermo-piezo-electromagnetic behavior of smart blades. VABS not only calculates the best structural and inertial properties for blade analysis, it also accurately recovers the 3D stress based on a simple 1D beam analysis. VABS code is commercially available through AnalySwift LLC and is extensively used in the helicopter and wind turbine industries. It is a highly efficient, finite-element based code which can provide detailed modeling of realistic composite blades in seconds using a laptop.

Research Objectives: Although the advanced capabilities of VABS do not exist in other rotor blade modeling tools, there remain physical aspects of realistic composite rotor blades that are not yet accounted for. Significant steps in achieving this can be met by the realization of the following objectives:

- Develop a higher-order asymptotic stress/strain recovery (GT task)
- Enable VABS to capture obliqueness in all the models (GT task)
- Develop a shear-deformable generalized Vlasov model (GT task)
- Modify VABS to include interaction of small parameters (GT task)
- Develop models for blades made of nonlinear materials (USU/Purdue task)
- Use the concept of representative structural element (RSE), recently named as Structure Genome (SG) to model rotor blades with span-wise heterogeneity (USU/Purdue task)
- Develop a multi-scale framework to rigorously model damaged blades (USU/Purdue task)

Accomplishments: As part of the current task, VABS as a tool has evolved in being able to provide diverse capabilities to accurately model rotor blades geometries considering both material and geometrical non-linearities. **S**ignificant progress on the GT sub tasks has been made on the higher-order stress/strain

recovery, obliqueness models, spanwise non-uniformity, tapered plates and dynamics of tapered beams, piezoelectric capabilities in shear sidesway problem and interaction of small parameters. Numerous attempts to identify the problem led to investigation of the different configurations of beam sections with different loadings. According to the current formulation in VABS, the principal axes of shear differ from principal axes in bending whereas 3D FEM results show them to be the same. Assuming 3D FEM results to be correct, the only conclusion that can be made is the sidesway problem arises due to the transformation from asymptotically correct strain energy to the Generalized Timoshenko (GT) model.

To address the problem of the interaction of small parameters, a theoretical framework was developed that considers the small parameters associated with the wall thickness a priori. Motivated by the shell-like nature of the problem, the generalized 3D strains can be represented as shell strains and curvatures or plate strains by means of a transformation between the two strain representations followed by process of dimensional reduction and evaluating warping zeroth and first order warping solutions. The approach involves suitable combination of plate and shell elements over the cross-section of the beam. Though this approach provides results in agreement with 3D FEM, it is not feasible to incorporate in the already existing VABS framework. To avoid this issue, Mechanics of Structural Genome (MSG), an approach developed at Purdue is considered which is explained later in this document. The sectional analysis consisting of thin-walled geometry leading to interaction of small parameters is discretized in a minimum number of smaller elements with aspect ratio that avoids this interaction, followed by a variational asymptotic approach on each of these elements along with appropriate continuity and boundary conditions.

To solve for the 3D displacements associated with a rotor blade, it is necessary to perform the 1D beam analysis after the 2D sectional analysis from VABS. As mentioned earlier, the current commercially released version of VABS is already equipped with piezoelectric analysis but the 1D beam analysis didn't allow to obtain correct results which account for this piezoelectric behavior. Another task, beyond the planned tasks, was completed where a modification to the fully intrinsic equations as well as the Geometrically Exact Beam Theory (GEBT) was carried out to assist a user in performing a complete and accurate rotor blade analysis equipped with piezoelectric materials.

Attempts have been made to include a physics based damping model to predict damping behavior of the rotor blade, thus avoiding the need to perform tests on new rotor blade designs. A theoretical formulation is developed based on Kelvin-Voigt model where dissipative forces are proportional to the strain rate and one dimensional damping loss factors, as it is shown to have a better co-relation with experimental results in the literature. Further, this work will be completed during the VLRCOE new task period.

The objective of USU/Purdue subtask is to enable VABS to go beyond linear, elastic, cross-sectional analysis by incorporating both material nonlinearity and geometry nonlinearity within the constitutive modeling. To achieve this objective,

significant progresses have been made in modeling blades with arbitrary spanwise heterogeneities through MSG, nonlinear elastic modeling including nonlinear shear and hyperelasticity has been developed within the VABS framework and continuum damage models have been developed to predict blades with damages.

MSG was developed through marrying the modeling philosophy of VABS and micromechanics to provide a unified framework for constitutive modeling of composite structures including beams, plates/shells, and 3D structures. In direct application to helicopter rotor blades, MSG provides a rigorous approach to handle composite blades with spanwise heterogeneity, not just taper with continuously changing cross-sections. It can handle any slender structures as long as the users want to model it as a beam. MSG also enables multiscale modeling, in other words, we now have the capability to directly link blade properties with the material level fiber/matrix details. The homogeneous layer assumption in previous VABS is not needed. It can also model stiffened composite panels.

Regarding nonlinear elastic modeling of composite blades, we have developed a systematic approach to handle beams made of hyperelastic materials. Both Trapeze effect and Poynting effect are systematically captured within one theory. Nonlinear constitutive relations for the beam are rigorously derived from 3D hyperelasticity. To capture the nonlinear shear effects of composites, an ad hoc constitutive model commonly accepted in the literature is introduced to obtain the material effects on the beam properties. A UMAT capability is also created for VABS so that users can provide their own customized nonlinear 3D material models.

Damage is inevitable in composite structures. We have started with traditional approach to capture the effects of matrix cracking on beam properties. Then we continued to a more rigorous approach based on continuum damage mechanics. VABS now can solve for not only the warping functions, blade properties, stresses, and strains, but also the damage, and hardening, softening, initiation, progression of failure of composite beams. It is found that VABS can accurately reproduce the direct numerical simulation results with orders of magnitude computing time saving.

To increase the user friendliness of VABS, we have also integrated VABS with ANSYS and ABAQUS so that realistic section can be created conveniently. Integrating VABS with CATIA is currently ongoing.

Students supported under the project:

1. Anurag Rajagopal (India): supported from 2011-2014 at GIT, PhD awarded May 2014, OptiStruct Developer, Altair Engineering, Inc., Irvine, CA.
2. Mohit Gupta (India): supported from 2014-2016 at GIT, currently pursuing PhD at Georgia Tech.

3. Fang Jiang (China): supported from 08/2012-08/2013 at Utah State University, then moved to Purdue, PhD awarded in May 2017. CAE Analyst, Copper Tire & Rubber Company, Findlay, Ohio.
4. Hemaraju Pollayi (India), postdoc (08/2011-08/2013) at Utah State University. Currently Associate Professor in GITAM University, India.

Patents/Software Invention Disclosures:

None

Publications:

<u>Theses</u>

1. <u>Rajagopal, A.,</u> Advancements in Rotor Blade Cross-Sectional Analysis Using the Variational-Asymptotic Method, PhD Thesis, Georgia Institute of Technology, April, 2014. **http://hdl.handle.net/1853/51877**
2. Jiang, F., Composite Beam Theory with Material Nonlinearities and Progressive Damage, PhD Thesis, Purdue University, May, 2017.

<u>Journal Papers</u>

1. Jiang, F.; Yu, W.; and Hodges, D. H.: "Analytical Modeling of Trapeze and Poynting Effects of Initially Twisted Beams," *Journal of Applied Mechanics*, vol. 82, 2015, 061003. doi: 10.1115/1.4030362

2. Hodges, Dewey H.: "Unified Approach for Accurate and Efficient Modeling of Composite Rotor Blade Dynamics," *Journal of the American Helicopter Society*," vol. 60, no. 1, 2015, article 01101, http://dx.doi.org/10.4050/JAHS.60.011001.

3. Sachdeva, C.; Gupta, M.; Hodges, D.H.; Modeling of Initially Curved and Twisted Smart Beams Using Intrinsic Equations, *International Journal of Solids and Structures,* accepted for publication on October 09, 2017.

4. Kovvali, R.K.; Hodges, D.H.; and Yu, W.: "Comment on 'An asymptotic analysis of composite beams with kinematically corrected end effects' by Jun-Sik Kim, Maenghyo Cho and Edward C. Smith [*International Journal of Solids and Structures*, 45, 2008, pp. 1954–1977]," *International Journal of Solids and Structures*, vol. 62, June 2015, pp. 269–270, http://dx.doi.org/10.1016/j.ijsolstr.2015.02.011.

5. Lee, Chang-Yong; and Hodges, Dewey H.: "Hybrid Transformation to a Generalized Reissner-Mindlin Theory for Composite Plates," *Journal of Applied Mechanics*, vol. 82, no. 9, Sept. 2015, article 091005, doi:10.1115/1.4030740.

6. Rajagopal, Anurag; and Hodges, Dewey H.: "Variational Asymptotic Analysis for Plates of Variable Thickness," *International Journal of Solids and Structures*, vol. 75-76, pp. 81–87, 2015, http://dx.doi.org/10.1016/j.ijsolstr.2015.08.002.

7. Jiang, F.; and Yu, W.: "Non-linear Variational Asymptotic Sectional Analysis of Hyperelastic Beams," *AIAA Journal*, vol. 54, 2016, pp. 679-690.

8. Kovvali, Ravi K.; and Hodges, Dewey H.: "Variational Asymptotic Modeling of Cosserat Elastic Plates," *AIAA Journal*, to appear, 2017.

9. Harish, Ajay; Harursampath, Dineshkumar; and Hodges, Dewey H.: "Model Reduction in Thin-Walled Open-Section Composite Beams Using Variational Asymptotic Method. Part I: Theory," *Thin-Walled Structures*, submitted, Oct. 2015.

10. Harish, Ajay; Harursampath, Dineshkumar; and Hodges, Dewey H.: "Model Reduction in Thin-Walled Open-Section Composite Beams Using Variational Asymptotic Method. Part II: Applications," *Thin-Walled Structures*, submitted, Oct. 2015.

11. Yu, W.: "A Unified Theory for Constitutive Modeling of Composites," *Journal of Mechanics of Materials and Structures*, vol. 11, no. 4, 2016, pp. 379-411.

12. Liu, X. and Yu, W.: "A Novel Approach to Analyze Beam-like Composite Structures Using Mechanics of Structure Genome," *Advances in Engineering Software*, vol. 100, 2016, pp. 238-251.

13. Peng, B.; A; Goodsell, J.; Pipes, R. B. and Yu, W.: "Generalized Free-Edge Stress Analysis Using Mechanics of Structure Genome," *Journal of Applied Mechanics,* vol. 83 (10), 2016, 101013.

14. Pollayi, H. and Yu, W.: "Modeling matrix cracking in composite rotor blades within VABS framework," *Composite Structures*, vol. 110, 2014, pp. 62-76.

15. Wang, Q. and Yu, W.: "A Variational Asymptotic Approach for Thermoelastic Analysis of Composite Beams," *Advances in Aircraft and Spacecraft Science*, vol. 1, 2014, pp. 93-123.

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17. Goodsell, J.; Peng, B.; Pipes, R. B.; and Yu, W.: "Interlaminar Stresses in Composite Laminates Subjected to Twisting Deformation," *Journal of Applied Mechanics,* vol. 84 (10), 2017, 104503.

18. Jiang, F. and Yu, W.: "Damage Analysis by Physically Nonlinear Composite Beam Theory," *Composite Structures*, vol. 182, 2017, pp. 652-665.

19. Liu, N. and Yu, W.: "Evaluation of Smeared Properties Approaches and Mechanics of Structure Genome for Analyzing Composite Beams," *Mechanics of Advanced Materials and Structures*, http://dx.doi.org/10.1080/15376494.2017.1330977.

Conference Papers:

1. Gupta, M. and Hodges, D.H.: "Modeling Thin-Walled Beams using VAM", 58th AIAA/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials

Conference, AIAA SciTech Forum, (AIAA 2017-1832). doi: 10.2514/6.2017-1832

2. Jiang, F. and Yu, W.: "A Beam Theory for Progressively Elastic Damage in Fiber-Reinforced Composite Structures," *Proceedings of the 57th Structures, Structural Dynamics, and Materials Conference*, San Diego, California, Jan. 4-8, 2016.

3. Jiang, F., Tian, S., and Yu, W.: "Nonlinear Modelling of Axially Deformable Elastica Based on Hyperelasticity," *Proceedings of the 57th Structures, Structural Dynamics, and Materials Conference*, San Diego, California, Jan. 4-8, 2016.

4. Peng, B.; A; Goodsell, J.; Pipes, R. B. and Yu, W.: "Generalized Free-Edge Stress Analysis Using Mechanics of Structure Genome," *Proceedings of the American Society for Composites 31st Technical Conference*, Williamsburg, Virginia, Sept. 19-22, 2016.

5. Peng, B. and Yu, W.: "Modeling Aperiodic Dimensionally Reducible Structures Using Mechanics of Structure Genome," *Proceedings of the American Society for Composites 31st Technical Conference*, Williamsburg, Virginia, Sept. 19-22, 2016.

6. Hoseini, Hanif S.; and Hodges, Dewey H.: "Joining 3-D Finite Elements to Variational Asymptotic Beam Models," 57th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, AIAA Science and Technology Forum 2016, San Diego, California, January 4 – 8, 2016.

7. Wang, Q.; Yu, W. and Sprague, M. A.: "Geometric Nonlinear Analysis of Composite Beams using Wiener-Milenkovic Parameters," *Proceedings of the 54th Structures, Structural Dynamics, and Materials Conference*, Boston, Massachusetts, Apr. 8-11, 2013.

8. Pollayi, H. and Yu, W.: "Modeling Matrix Cracking in Composite Rotor Blades within VABS Framework," *Proceedings of the 54th Structures, Structural Dynamics, and Materials Conference*, Boston, Massachusetts, Apr. 8-11, 2013.

9. Yu, W.: "Cross-sectional Analysis of Composite Beams with Distributed Loads," *Proceedings of the 32nd ASME Wind Energy Symposium*, National Harbor, Maryland, Jan. 13-17, 2014.

10. Valliappan, V.; Harursampath, D.; Roy, S. and Yu, W.: "Cross-sectional Modeling of an Initially curved and pre-twisted smart beam," *Proceedings of the 22nd AIAA/ASME/AHS Adaptive Structures Conference*, National Harbor, Maryland, Jan. 13-17, 2014.

11. Yu, W.: "Structure Genome: Fill the Gap between Materials Genome and Structural Analysis," *Proceedings of the 56th Structures, Structural Dynamics, and Materials Conference*, Kissimmee, Florida, Jan. 5-9, 2015.

12. Jiang, F. and Yu, W. "Non-linear Sectional Analysis of Composite Beams with Finite Deformation and Hyperelastic Materials," *Proceedings of the 56th*

Structures, Structural Dynamics, and Materials Conference, Kissimmee, Florida, Jan. 5-9, 2015.

13. Liu, N. and Yu, W.: "Loss of Accuracy Using Smeared Properties in Composite Beam Modeling," *Proceedings of the American Society for Composites 30th Technical Conference*, East Lansing, Michigan, Sept. 28-30, 2015.

Awards:

<u>Faculty Technical Awards:</u>

1. Dewey Hodges, AIAA SDM Award, 2017
2. Dewey Hodges, Spirit of St. Louis Medal (ASME), 2015
3. Dewey Hodges, Alexander A. Nikolsky Honorary Lectureship (AHS), 2014
4. Dewey Hodges, Ashley Aeroelasticity Award (AIAA), 2013
5. Dewey Hodges, Keynote lectures at several conferences starting in May 2013
6. Dewey Hodges, Elected Fellow, ASME, 2014 (already fellow of AAM, AHS, AIAA)
7. Wenbin Yu, Elected Fellow of ASME, 2013
8. Wenbin Yu, Keynote lectures and invited seminars at several places starting in May 2012

<u>Student Technical Awards:</u>

1. Mohit Gupta, Charles C. Crawford Scholarship, Vertical Flight Foundation (AHS), 2016.
2. Dr. Klaus-Körper Foundation RCM Scholarship awarded by International Association of Mathematics and Mechanics, 2016.
3. Mohit Gupta, Winner, Airbus Innovation Showdown, Mobile, AL, 2016
4. Mohit Gupta, Don Toler Scholarship, Vertical Flight Foundation (AHS), 2015.
5. Mohit Gupta, Global Champion, Airbus Fly Your Ideas, Hamburg, Germany, 2015.

Technology Transfer:

None to report

Task 1.2 (GT-3): Advanced Turbulence and Transition Simulation Techniques for Rotorcraft

PIs: Marilyn J. Smith (Georgia Tech), Suresh Menon (Georgia Tech)

Background: To achieve design and analysis goals for rotorcraft, the underlying numerical and physical uncertainties from turbulence and transition modeling must be identified and minimized. Rotorcraft simulations indicate that URANS turbulence models are failing to provide consistent accuracy when the flow field includes complex viscous features, such as transition and separation. Transition models fail to capture physical boundary layer behavior prior to separation. These poor correlations are not surprising as the models are statistical approximations of the turbulence scales or representations of transition zones that include constants tuned to a small set of test cases, few if any of which include the complex physics encountered in rotary-wing configurations. Large Eddy Simulation (LES) and direct numerical simulation (DNS) are able to resolve the most energetic scales that dictate the turbulent behavior encountered in these flows. LES is capable of capturing the larger eddies and models the smallest or subgrid-scale (sgs) eddies. Unfortunately, these approaches require significantly larger grids and restrictive time steps that scale nonlinearly with increasing Reynolds number. Hybrid RANS-LES and RANS-LES-DNS approaches, including transition, have the potential to significantly advance the ability of aerodynamic and aeroelastic computational solvers to design and analyze rotorcraft. These include both current vehicles and advanced designs to meet DoD and NASA S&T goals.

Research Objectives: The primary objectives of this effort are focused on the development and implementation of LES-based turbulence methods with compatible transition models that can be implemented in current and future URANS-based solvers. These objectives include two development tracks for short and long term methods: improved hybrid RANS/LES and new hybrid RANS/LES/DNS, respectively. In addition to the development of these methods, improvements of current turbulence and transition methods will be actively sought. The overarching goal in the development of these new turbulence methods is to provide future algorithms that more accurately resolve complex issues for the aerodynamics (e.g., vibration, fatigue, dynamic stall), and flow field physics (e.g., interactional aerodynamics) that are still not resolved by state-of-the -art computational techniques.

Accomplishments: The techniques proposed here have significant advantages over current approaches that focus on tasks to extend URANS models by adding correction terms for rotation, separation, and other phenomena. The approach is innovative as they are both consistent and conservative.

This proposal has a two-pronged approach. The first track will focus on initial development efforts using an in-house rigorous LES solver to ensure that the development of the methods is not compromised by numerical inaccuracies found within URANS codes. The modeling of transition to turbulence will take advantage of scale-similar dynamic evaluation of the near wall production used in

LES closure and will combine it with a transport model for intermittency. This approach will be seamlessly coupled to the LES localized dynamic procedure using the hybrid closure developed earlier so that both the transition process & location and near-wall turbulence evolution will be captured within a single dynamic formulation Validation cases will include, but not be limited to, airfoils and wings in static and dynamic stall, as well as canonical configurations such as rotating cylinders and spheres.

The second parallel effort will focus on formulation, implementation and demonstration of these methods as well as exploration/extension/modification of existing transition models with LES-based turbulence methods within state-of-the-art RANS solvers. These modifications may include aspects regarding boundary conditions and implicit time stepping, as well as the problems encountered with higher numerical dissipation and lower-order spatial/temporal algorithms compared to LES methods. The emphasis on this track will be to develop a model that captures more of the physics of the wall-bounded flows, but deals with the more practical aspects of the hybrid RANS-LES model for engineering applications. In addition, rotorcraft configurations with test data (UH60A, HARTII, mod-Robin, hubs) will be used.

In track one, a hybrid two-level simulation – large eddy simulation (TLS-LES) turbulence closure has been developed and demonstrated to be multi-scale and a robust approach for simulation of high Reynolds number turbulent flows. The method has been used to study simple to complex flows at moderate to high Re, including wall-bounded flows, free-shear flows, wakes, separating/reattaching flows, swept flows etc. A unique ability of the TLS model is that it provides information about the small-scales of motion, which in turn can be used to assess and verify assumptions of the conventional LES closures. Therefore, two well-established high Re DNS datasets were used to examine the small-scale turbulence physics in an a priori manner. These datasets included, a forced isotropic turbulence, and a fully developed turbulent channel flow, which are canonical configurations and know to exhibit different types of large-scale and small-scale turbulence dynamics. The analysis revealed presence of several characteristics of small-scale turbulence, which are usually neglected by the conventional LES approaches. In particular, behavior of energy transfer mechanism, type of turbulent transport of momentum and small-scale vorticity was examined showing that the TLS model can accurately account for such small-scale physics of turbulent as it does not employ the notions of eddy viscosity, co-gradient turbulent transport, and a forward cascade of energy. To further assess the ability of the TLS model, a posteriori analysis was performed by examining the small-scale solution obtained from TLS-LES of a high Re fully developed turbulent channel flow. Both a priori and a posteriori analysis demonstrated consistency of the TLS method in capturing physics of LS and SS and their interactions. The results from such analysis indicated that conventional LES formulations can be further improved. For example, ability to account for backscatter and both types of turbulent transport rely on a better representation of the SGS stress tensor. Therefore, conventional models can be improved along the lines of the "mixed models" for the SGS tensor, where it can be defined in

terms of two terms, one using eddy viscosity based formulation, and the other that does not employ a co-gradient assumption, which can also account for backscatter of TKE. This is important for high Re flows where the TLS-LES can be used for computational efficiency, and an improved LES formulation can be blended with the TLS method for better predictive capabilities. Such an approach for mixed model based LES will be examined in a future study. Another important aspect of the flows observed in rotorcraft system is presence of transition to turbulence. Currently, the TLS model is being assessed for its capabilities to capture laminar to turbulent transition by considering a spatially evolving laminar boundary layer, which is perturbed by TS wave through suction and blowing approach.

There has been extensive evaluation of the locally dynamic kinetic model (LDKM) for the hybrid RANS-LES approach (HRLES) in several URANS/LES solvers. Originally FUN3D and OVERFLOW were the baseline solvers, and OpenFoam was added to permit a non-US student to work on the task, but this proved to be an inefficient use of resources. In Year 3 a simple in-house URANS/LES solver (GTSim) to permit rapid evaluation and prototyping was developed with cost-share and some leveraged funding, and in Year 4 it was successfully applied to a number of studies to accelerate progress. Results show significant improvement in capturing the unsteady physics over URANS, DES, and HRLES for both canonical and rotorcraft applications. In particular, the new HRLES solver was able to successfully advance physics associated with static and dynamic stall in reverse flows using high-fidelity experiments in collaboration with a VLRCOE task from UMD (Jones). Efforts in Year 5 improved details of the tHRLES model including modifications to the hybrid term to maintain LES during quiescent separated flows and a new filter to reduce dissipation to capture more of the unsteady phenomena. Clear demonstration of the ability of the HRLES and tHRLES models to capture unsteady, separated wakes over DDES models was demonstrated and published in the AHS. Various cross-flow models have also been studied, and their ability to capture three-dimensional flows on fuselages has been demonstrated with tHRLES. An unstructured version of tHRLES was developed, implemented, and validated within the NASA FUN3D solver, with publications planned for January 2018. GTSim's tHRLES capabilities have been extended to incompressible formulations and multiblock formulations to permit assessment of complex flows such as active flow control. Demonstration within Helios with FUN3D as the near-body solver has been accomplished for complex, separated hub flows and dynamic stall applications. Additional evaluation of the impact and modeling of nonlinear gusts, free-stream and wake-generated turbulence is underway; the remainder of this effort will be leveraged via continuing projects (with co-PI Anya Jones at UMD).

Students supported under the project:

1. Joachim Hodara (France): supported ~50% time for PhD 2013-2016 at GIT, PhD awarded May 2016, CFD Developer, Dassault Systemes, Providence, RI

2. Daniel Prosser (USA): supported ~40% time in 2013-2014 to develop HRLES in FUN3D for highly separated flows; PhD awarded August 2015, Aeronautical Engineer, US Navy, Patuxent River, MD.
3. Philip Cross (USA): supported ~40% time from mid-2015-2017 at GIT, currently pursuing PhD; efforts will be part of PhD thesis.
4. Amanda Grubb (USA): supported 10% time in 2017 to transition to unstructured solvers (FUN3D), currently pursuing PhD, expected to graduate in Dec. 2018; efforts will be part of PhD thesis
5. Nicholson Koukpaizan (Benin): supported 33% time in 2016-2017 to continue development of transition and turbulence model for use in advanced applications, currently pursuing PhD; efforts will be part of PhD thesis.
6. Nicolas Reveles (USA): supported ~50% time in 2011-2012. Early work with HRLES in OVERFLOW; PhD awarded May 2014; Aerospace Engineer, ATA Engineering, Huntsville, AL.
7. Marin Butori (France): supported ~20% in 2016 to parallelize GTSim; MSAE awarded in May 2017; Engineering consultant, New York, NY.
8. Adam Bern (USA): supported 20% in 2017 to extend GTSim to study advanced turbulent applications; currently pursuing MS/PhD at Georgia Tech; efforts will be part of MS project and PhD thesis.
9. James Clinton (USA): undergraduate, class credit; one semester, 2016.
10. Avani Gupta (India): undergraduate intern, 2016.
11. Louis Boile (France): undergraduate, visiting scholar; two semesters, 2014.
12. Maitreya Venkataswamy (USA): undergraduate, 2 semesters, 2016-1017.
13. Tobias Gibis (Germany): graduate, 1 semester, 2017.
14. Deban L. Thanki (India): graduate, 1 semester, 2015.
15. Siva Mani (India): graduate, 2 semesters, 2016-2017.

Patents/Software Invention Disclosures:

Software Disclosures for tHRLES (Menon, Sanchez-Rocha, Hodara, Smith, Grubb) in 2017 to facilitate transition to FUN3D. NASA Software Disclosure will be filed when GT one is approved.

Publications:

<u>Theses</u>

1. Hodara, Joachim, *Hybrid RANS-LES Closure for Separated Flows in the Transitional Regime*, PhD Dissertation, Georgia Institute of Technology, April 2016, http://hdl.handle.net/1853/54995
2. D. T. Prosser. Advanced Computational Techniques for Unsteady Aerodynamic–Dynamic Interactions of Bluff Bodies. PhD thesis, Georgia Institute of Technology, Atlanta, Georgia, 2015. https://smartech.gatech.edu/handle/1853/53899.
3. Reveles, Nicolas, Advanced Methods for Dynamic Aeroelastic Analysis of Rotor*s*, PhD Dissertation, Georgia Institute of Technology, May 2014, https://smartech.gatech.edu/handle/1853/51904

Journal Papers

1. C. E. Lynch and M. J. Smith. "Extension and Exploration of a Hybrid Turbulence Model on Unstructured Grids", *AIAA Journal*, 49(11):2585– 2591, 2011.
2. R. Ranjan and S. Menon, "A Multi-Scale Simulation Method for High Reynolds Number Wall-Bounded Turbulent Flows", *Journal of Turbulence,*14, 2013.
3. R. Ranjan and S. Menon, "A Dynamic Two-Level Large-Eddy Simulation Method for High Reynolds Number Flows", *Bulletin of the APS*, 58, 2013.
4. R. Ranjan and S. Menon, "On the Application of the Two-Level Large-eddy Simulation Method to Turbulent Free-shear and Wake Flows", *Journal of Turbulence*, 16, 2015.
5. J. Hodara and M. J. Smith, "Hybrid Reynolds-Averaged Navier–Stokes/Large-Eddy Simulation Closure for Separated Transitional Flows", AIAA Journal, 55(6):1948–1958, 2016.
6. Reich, D., Shenoy, R., Schmitz, S., and Smith, M. J., "A Review of 60 Years of Rotor Hub Drag and Wake Physics: 1954 – 2014," *Journal of the American Helicopter Society*, Vol. 61, pp. 022007, 1–17, January, 2016. DOI:10.4050/JAHS.61.022007
7. J. Hodara, A. Lind, A. Jones, and M. J. Smith., "Collaborative Investigation of the Aerodynamic Behavior of Airfoils in Reverse Flow", Journal of Aircraft, 61(2):032001, 2016.
8. R. Ranjan and S. Menon, "Vorticity, Backscatter and Counter-gradient Transport Predictions using Two-level Simulation of Highly Turbulent Flows", Under Review, *Journal of Turbulenc*e, 2017.

Conference Papers:

1. Rocha, M., Germano, M. and Menon, S., "Hybrid RANS/LES Equations," 64th Annual APS-DFD Meeting, Baltimore, MD, Nov 20-22, 2011.
2. J. Cook, M. Sanchez-Rocha, R. Shenoy, M. J. Smith, and S. Menon, "Improved Prediction of Complex Rotorcraft Aerodynamics, Proceedings of the American Helicopter Society 69th Annual Forum," Phoenix, AZ, May 21–23 2013.
3. Abba, A., Rocha, M., Menon, S., and Germano, M., "Hybrid RANS/LES for High Reynolds Number Turbulent Flows," 8th Turbulent and Shear Flow Phenomenon, Aug 2013.
4. R. Ranjan and S. Menon, "Multi-Scale Simulations of Turbulent Wall-Bounded and Wake Flows," AIAA 2014-1447*,* January 2014.
5. J. Hodara and M. J. Smith, "Improvement of Crossflow Aerodynamic Predictions for Forward Flight," Proceedings of the 40th European Rotorcraft Forum, Southampton, UK, Sept. 2–4 2014.
6. J. Hodara, A. Lind, A. Jones, and M. J. Smith, "Collaborative Investigation of the Aerodynamic Behavior of Airfoils in Reverse Flow," Proceedings of the American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May 2015.

7. S. Menon and R. Ranjan, "A Priori and a Posteriori Analysis of the Hybrid Two-Level Large-Eddy Simulation for High Reynolds Number Flows," 15th European Turbulence Conference, Delft, Netherlands, 2015.
8. J. Hodara and M. J. Smith. Improved Turbulence and Transition Closures for Separated Flows. Proceedings of the 41st European Rotorcraft Forum, Munich, Germany, September 1–4 2015.
9. P. Cross, J. Hodara, and M. J. Smith. Evaluation of Crossflow Transition Models for Rotorcraft Applications. Proceedings of the 72nd AHS Annual Forum, West Palm Beach, FL, May 17–19 2016.
10. L. Smith, A. Lind, K. Jacobson, M. J. Smith, and A. Jones. Experimental and Computational Investigation of a Linearly Pitching NACA 0012 in Reverse Flow. Proceedings of the 72nd AHS Annual Forum, West Palm Beach, FL, May 17–19 2016.
11. Grubb and M. J. Smith. Assessment of an Unstructured Transitional Hybrid RANS-LES Methodology (Invited Special Session), to be presented at the AIAA Science and Technology Forum and Exposition, Kissimmee, FL, January 8–12 2018.

Awards:

Project Technical Awards:

1. Hodara, Lind, Jones, and Smith, Best Paper, Aerodynamics, American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May, 2015.

Faculty Technical Awards:

1. Marilyn Smith, Agusta-Westland International Fellowship Award (AHS, HART-II Workshop), 2012
2. Marilyn Smith, Agusta-Westland International Fellowship Award (AHS, US/France PA), 2014
3. Marilyn Smith, American Helicopter Society Technical Fellow, 2015
4. Marilyn Smith, AIAA Fellow, 2015
5. Marilyn Smith, NASA Group Achievement Award (FUN3D Development Team, rotorcraft contributions), 2017
6. Marilyn Smith, Invited seminars at several places 2011-2017
7. Suresh Menon, Hightower Professor in Engineering, 2013-present
8. Suresh Menon, Fellow, American Association for the Advancement of Science, 2013

Student Technical Awards:

(See Task 10B for Daniel Prosser's and Task 22 for Philip Cross' awards)

1. Joachim Hodara, MS Scholarship, Vertical Flight Foundation (AHS), 2013.
2. Joachim Hodara, PhD Scholarship, Vertical Flight Foundation (AHS), 2014.
3. Joachim Hodara, Intern, Dassault Systemes, Providence, RI, Summer 2015
4. Joachim Hodara, "A Consistent Hybrid URANS/LES Approach with Transition for Rotorcraft," 2014 Lichten competition, 2014 Southern Region Lichten

Competition Winner

5. Amanda Grubb, MS Scholarship, Vertical Flight Foundation (AHS), 2015.
6. Amanda Grubb, PhD Scholarship, Vertical Flight Foundation (AHS), 2016.
7. Amanda Grubb, Georgia Tech President's Fellow, 2014-2017.
8. Amanda Grubb, Intern, AFDD, AMRDEC, Moffatt Field, CA, Summer 2015
9. Amanda Grubb, Intern, NASA-LaRC, Hampton, VA, Summer 2016
10. Amanda Grubb, Intern, AED, AMRDEC, Huntsville, AL, Summer 2017

Technology Transfer:

Solvers available in FUN3D and OVERFLOW (upon request) solvers. Technology transfers through student internships (see Student Technical Awards). Collaborations with Sanchez-Rocha (Dassault), Germano (Milan), Fureby (FOI, Sweden), Jain (AFDD), Costes/LePape/Richez (ONERA), Gardner/Richter (DLR), Jacobson (NASA), Cook (StarCym LLC), Shenoy (Craftech).

Task 1.3 (GT-4): Improvements to a Methodology for the Prediction of Rotor Blade Ice Formation and Shedding

PI: Lakshmi N. Sankar (Georgia Tech)

Background: Operation of rotorcraft under icing conditions is an interdisciplinary problem that affects the availability, affordability, safety and survivability of the vehicle. Availability of the vehicle may also be compromised if the ice formation re-quires excessive torque to overcome the drag to operate the rotor. Affordability is affected by the power requirements and cost of ownership of the deicing systems needed to safely operate the vehicle. In order to ensure safety, ice shedding should also be addressed, in addition to ice accretion, run back and refreeze.

Modeling the physics of this complex phenomenon requires tools from the disciplines of computational fluid dynamics, computational structural dynamics, ice accretion models, deicing models, and ice shedding models. The individual modules need to be robust, compatible with each other through industry-standard open file I/O methods, and should be modular in order to allow the replacement of the individual modules with more advanced modules as technology matures. The coupled analysis should be been applicable to 2-D airfoils, airframe, and 3-D rotors in hover and forward flight under icing conditions, and well correlated with test data.

Research Objectives: The objective of this research is to remove many of the limitations and empiric-ism inherent in existing icing, deicing, and shedding models.

- The 2-D strip theory analysis within LEWICE3D will be augmented with a fully three-dimensional unsteady approach for the external layers of ice, water, and air as well as the internal airframe structure with embedded heater elements.

- A coordinated validation of the improved tools will be done in partnership with our industry partners at Sikorsky, Bell, Boeing; Army and NASA scientists, and university partners at PSU. These validation studies will use wind tunnel and flight test data acquired by our research partners.

Technical approach: Fundamental research in the physics of ice formation, runback refreeze, conjugate heat transfer, and shedding will be done with the approach shown in the figure below, with enhancements to LEWICE-3D listed below.

PYTHON Framework
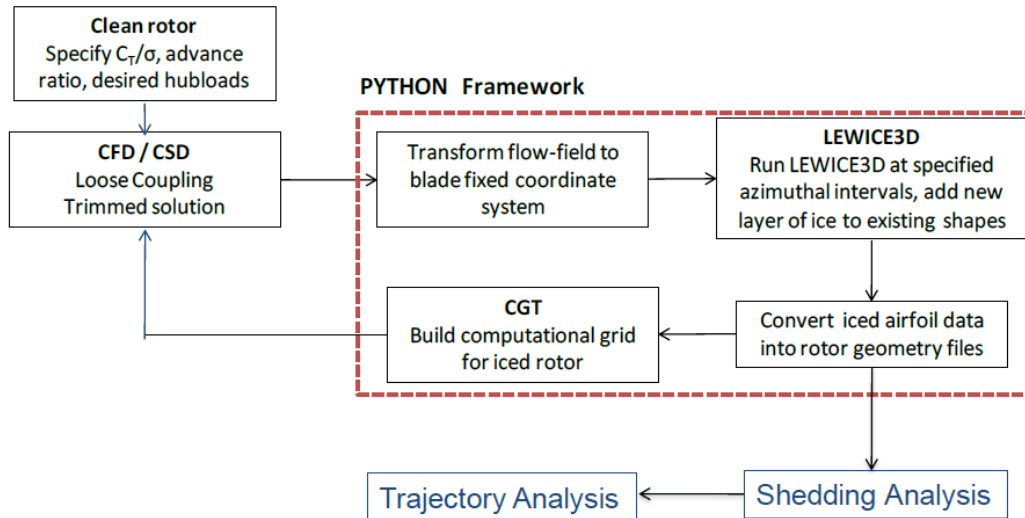
In many of the existing analyses, the accumulation of water mass on the rotor/airframe is presently computed using a Lagrangian approach, where the water molecules are transported by a steady flow field. This limitation on steady flow (suitable only for aircraft applications) will be replaced by an Eulerian transport of the water particles through an unsteady flow field. This should lead to better estimates of the collection efficiency, a fundamental factor in ice accretion. Comparisons with Lagrangian efforts will be done.

In many of the existing analyses, the boundary layer growth, transition, and surface heat transfer rate are modeled using quasi-steady empirical models. A 3-D unsteady multi-species transport approach over the airframe and rotor surface will be developed that models the ice build-up in a fully 3-D unsteady manner. State of the art transition models, e.g. ones that use transport of an intermittency factor, will be explored for a better prediction of flow transition within the surface and water layers in order to better estimate the surface skin friction and heat transfer rates.

In many of the existing analyses (and related deicing and anti-icing codes), the heat transport within solids is done using quasi-steady strip theory approaches. The blade is divided into strips or segments, and the heat transfer phenomenon within the solid is modeled. The heat transfer rate is matched with that at the water/air layer on the outside. In reality, the heat transport phenomena within the solid and in the boundary layer outside are influenced by localized heater elements and considerable non-uniformity in temperature distribution and heat transfer rate occur. These phenomena should be better understood and modeled in a fully 3-D fashion for the proper design of deicing systems and assess transient operations (heater on/off).

Shedding of ice is also of concern. Existing models use a simple 1-D force balance of the centrifugal, pressure, surface adhesion, and cohesion forces to predict shedding. More accurate 3-D approaches that acknowledge the spatial irregularities of the ice are needed and will be developed.

Accomplishments: A 3-D collection efficiency model has been developed that receives flow field information from industry software (OVERFLOW, GT-Hybrid) and outputs the amount of water mass per unit time, entering the boundary layer. An extended Messinger model for ice accretion has been developed that replaces empirical skin friction data with CFD based skin friction data. A fully 3-D time-dependent deicing analysis has been developed for the rotor structure and embedded heating elements. Validation of the individual modules has been done using 2-D test data. The integrated suite has been applied to a 3 bladed teetering rotor recently tested at NASA Glenn Research Center. Encouraging preliminary results have been obtained for the ice formation and growth, surface temperature distributions during the deicing cycle, and the attendant rise in power and loss of thrust. These modules have been made available to industry partners.

Work was also done on the integration of the present analyses into the HELIOS framework. Python scripts were developed for fully integrating these tools into HELIOS framework with the assistance of Dr. Andrew Wissink. These scripts were evaluated on a distributed cluster environment, where the various modules store and exchange data from a shared memory.

Preliminary work was also done to assess the ability of the tools for modeling coaxial rotor configurations.

Students supported under the Project:

1. Elia Wing (Aero Design Engineer at GE Aviation, Cincinnati, OH)
2. Dr. Jeewoong Kim (ART, Inc.)
3. Dr. Ritu Marpu (CD-Adapco)
4. Dennis Garza (Aerospace Engineer at Mercer Engineering Research Center; previously at Bell Helicopter Textron)
5. Stephen Marone (Assistant Project Manager at Extreme Flight, United Arab Emirates)
6. Nana Obayashi (Graduates with an MSAE in Dec 2016; Green card holder).

Patents/Software Invention Disclosures

None

Faculty Awards

1. American Helicopter Society 2014 Howard Hughes Award (Team member, Research on Helicopter Icing)

Publications

Theses

1. Kim, J., "Development of a Physics Based Methodology for the Prediction of Rotor Blade Ice Formation," Ph.D. Dissertation, Georgia Institute of Technology, 2015. https://smartech.gatech.edu/handle/1853/54390

Journal Papers

None

Conference Papers

1. Kim, J. W., Garza, P. D., Sankar, L. N., Kreeger, R. E., "Ice Accretion Modeling Using an Eulerian Approach for Droplet Impingement," AIAA 2013-0246.
2. Kim, J. Sankar, L. N., Palacios, J., and Kreeger, Richard E., "Assessment of Classical and Extended Messinger Models for Modeling Rotorcraft Icing Phenomena," 40th European Rotorcraft Forum, 2014.
3. Ali, M., and Sankar, L. N., In-Cloud Ice Accretion Modeling on Wind Turbine Blades Using an Extended Messinger Model," AIAA 2015-3715.
4. Kim, J. Sankar, L. N., Palacios, J., and Kreeger, Richard E. "Numerical and Experimental Studies of Rotorcraft Icing Phenomena," 41th European Rotorcraft Forum, 2015.
5. Kreeger, R. E., Sankar, L. N., Nucci, M., and Kunz, R., "Progress in Rotorcraft Icing Computational Tool Development," SAE Technical Paper 201501-2088, 2015.
6. Sankar, L. N., Kim, J. W., Bain, J., Wissink, A., and Kreeger, R. R., "Integrated Tools for Rotorcraft Icing Analysis," AHS 72nd Annual Forum, West Palm Beach, Florida, USA, May 17-19, 2016.

Technology Transfer:

Software modules (3-D collection efficiency module, ice accretion module using an extended Messinger model, 2-D/3-D deicing module, Teetering Rotor Trim under icing) have been transferred to industry.

Task 1.4 (GT-7): Finite-State Inflow Modeling for Multi-Rotor and Compound Rotorcraft Configurations and Evaluating High-Speed Rotor Performance in Army and Naval Operations

PIs: David A. Peters (Washington University), J.V.R. Prasad (Georgia Tech)

Background: Multi-rotor configurations and their analysis to support Army and Naval Operations pose challenges to inflow modeling due to: (1) Rotors operating at very high advance ratio, (2) fully or partially overlapped multiple rotors, (3) rotor wake interference on wings and pusher propellers/ducted fans, (4) effect of wake distortion in maneuvering flight, (5) rotors in close proximity to moving ship deck/superstructure, and (6) rotors continuously operating in autorotation state (e.g., Heli-plane).

Pilot-in-the-loop simulation requires tractable real-time inflow models, and inflow dynamic coupling with rotor/body dynamics in the extracted linear models is important for stability and control analysis and control law design. Recent developments in the finite-state dynamic wake model provide opportunities to advance the state of the art of the rotor inflow modeling for flight mechanics simulation due to closed form velocities below disk. This is because we now have a closed-form solution for all three components of the flow everywhere in the field, including below the plane of the rotor disk both in-wake and out-of-wake. The challenge, however, is that this new solution requires computations of the co-states (i.e., the adjoint of the velocity). We will need to find an efficient means of doing this in real time.

In a related challenge, present rotor systems in forward flight produce 6 to 10 times the minimum induced power predicted by Glauert. An understanding of why this is the case could provide insight for new ways to design and operate rotors for greater efficiency, longer range, and larger payload. This could be through hardware changes, design variations, etc.

Research Objectives: The following are the research objectives of the project:
- Development of finite-state inflow models for multi-rotor configurations capturing rotor-rotor interference. This implies correlations with available test data.
- Determine computational efficiency of finite-state models in terms of inflow model order so that one can determine *a prior* necessary model fidelity and in real time simulation.
- Use of finite state inflow models to capture the nature of rotor performance. We especially want to study from a theoretical, potential flow standpoint where the various sources of induced power come from. Such a determination will, by implication, imply the hardware and/or operational parameters necessary to improve efficiency. Part of this would be ideas on how to trim existing rotors to achieve lower induced power.
- Achieve significant technology transitions to government and industry.

Accomplishments: Development of inflow models of new configurations such as co-axial and tandem was accomplished by treating each rotor as a pressure discontinuity in the flow filed and accounting for rotor-to-rotor interference through the nonlinearities and the flow off the disk. The new inflow results from the previous RCOE tasks provided the framework for doing this.

Utilization of classical quadratic optimization theory in conjunction with the closed-form finite state model and various constraints (representing hardware and operational limitations) was employed in order to determine sources of losses. In addition, effects due to finite number of blades, realistic inflow feedback, reversed flow, root cut-out, not treated in earlier work were modeled and analyzed.

Model validations were carried out through correlations with available test data such as: (1) wind tunnel data of induced velocities at and off rotor disk, and (2) rotor load measurements in steady trimmed flight.

Transition of the developed inflow models to industry was accomplished through technical collaborations.

The following is a list of accomplishments during each year of the project:

Year 1:
- *Rotor Optimum Performance:* Developed a finite state wake formulation for estimation and optimization of rotor induced power; Investigated effects due to wake swirl and finite number of blades on rotor induced power; Correlated new model predictions with Goldstein's theory results in axial flight.
- *Multi-Rotor Dynamic Inflow Modeling:* Developed an adjoint method for off-disk inflow modeling below the rotor in closed form; Developed co-axial rotor inflow models for hover and correlated them using the AFDD co-axial rotor test data.

Year 2:
- *Rotor Optimum Performance:* Evaluated a finite state wake formulation for estimation and optimization of rotor induced power.
- *Multi-Rotor Dynamic Inflow Modeling:* Developed a blended model for better inflow convergence; Developed co-axial rotor inflow models for steady forward flight and correlated with wind tunnel performance test data of a coaxial rotor from the literature.

Year 3:
- *Rotor Optimum Performance:* Development of formulas for effect of blade number; Addition of effect of inflow feedback on performance; Fuller understanding of convergence on correlation.
- *Multi-Rotor Dynamic Inflow Modeling:* Correlation with Harrington co-axial rotor test data; Development of model in terms of He variables; Complete blending model good at all skew angles; Addition of nonlinear terms to the full inflow model.

Year 4:
- *Rotor Optimum Performance:* Converged solution with the inflow feedback, addition of reversed flow, addition of root cut out and blade tip loss factor
- *Multi-Rotor Dynamic Inflow Modeling:* Completion of blended method for axial velocity, completion of blended method for in-plane velocity, both valid above

rotor disk, on rotor disk, and below both in and out of wake; Analysis of significant differences between Active and Receiving Rotor Inflow Model (ARRIM) and a vortex-based inflow mode; Extraction of appropriate ARRIM correction terms.

Year 5:

- *Rotor Optimum Performance:* Completion of (a) Finite number of blades with rubber rotor (b) Finite number of blades without reverse flow (c) Finite number of blades with reverse flow.
- *Multi-Rotor Dynamic Inflow Modeling:* Completion of (a) Corrections to analytical coaxial rotor inflow model identified using free-wake model solutions (b) Analytical approach to predict rotor-to-rotor dynamic interactions in a coaxial rotor configuration.

Students and Researchers supported under the Project:

1. Dr. Chad File, Ph.D., Washington University, 2013. Presently a Professor at Anderson University, Anderson, Indiana.
2. Dr. Zhongyang Fei, Ph.D., Washington University, 2013. Presently a Professor at Harbin Institute of Aeronautics, China.
3. Ramin Modarres, M.S. 2013, Washington University. Went onto Ph.D. program.
4. Morgan Nowak, M.S., Georgia Tech, 2014. Discontinued PhD program at Georgia Tech due to personal reasons.
5. Dr. Jianzhe Huang, Ph.D., Washington University, 2015. Presently at Caterpillar Tractor, Peoria, Illinois.
6. Yong-Boon Kong, Ph.D. student (expected graduation: 2018), Georgia Tech
7. Fayyaz Guner, Ph.D. student (expected graduation: 2020), Georgia Tech

Students worked on the Project but not supported:

1. Dr. Xialing Ulrich, Ph.D., Washington University, 2012.
2. Tyler Willibrand, B.S., Washington University, 2011.
3. Jesse Chugani, B.S., Washington University, 2012.
4. Benjamin Rahming, B.S., Washington University, 2013.
5. Patra Sayan, B.S., Washington University, 2014.
6. Adam Cooperberg, B.S., Washington University, 2014.
7. Sang Hyun Bae, B.S., Washington University, 2014.
8. William Luer, B.S., Washington University,2015.
9. Karankumar Sutaria, B.S., Georgia Tech, 2015.

Patents/Software/Invention Disclosures:
None

List of publications:

Theses:

1. File, Chad, *Optimization of Induced Power from Dynamic Inflow Theory with Realistic Constraints*, Ph.D. Thesis, Washington University, May 2013.
2. Fei, Zhongyang, *Complete Flow Around a Rotor with Lift and Mass Injection*, Ph.D. Thesis, Washington University, May 2013.

3. Modarres, Ramin, *Ideal Optimum Performance of Propellers, Lifting Rotors, and Wind Turbines*, Master of Science Thesis, Washington University, August 2013.
4. Huang, Jianzhe, *Potential-Flow Inflow Model Including Wake Distortion and Contraction*, Ph.D. Thesis, Washington University, May 2015.
5. Hong, JunSoo (Sean), *Optimum Rotor Power in Complex Flow Environments*, Ph.D. Thesis, Washington University, May 2017.

Journal Papers:

1. Peters, David A. and Modarres, Ramin, "A Compact Closed-Form Solution for the Optimum Induced-Flow Distribution of an Ideal Wind Turbine," Wind Energy Journal, Volume 17, Issue 4, April 2014, pp. 589-603.
2. Huang, Jianzhe, Nowak, Morgan, Peters, David, and Prasad, J.V.R., "Converged Velocity Field for Rotors by a Blended Potential Flow Method," The Journal of Aviation Technology, Vol. 1, No. 2, Nov. 2014.
3. Modarres, Ramin and Peters, David. A., "Optimum Performance of an Actuator Disk by a Compact Momentum Theory Including Swirl," *Journal of the American Helicopter Society*, Vol. 60, No. 1, January 2015, pp. 012003-1 through 012003-10.
4. Fei, Zhongyang, and Peters, David A., "Fundamental Solutions of the Potential Flow Equations for Rotorcraft with Applications," *AIAA Journal*, Volume 53, No. 5, May 2015, pp. 1251-1261.
5. Fei, Zhongyang and Peters, David A., "Applications and Data of Generalized Dynamic Wake Theory of the Flow in a Rotor Wake," *IET Control Theory and Applications*, CTA-SI-2014-0710.R1; Vol. 9, No. 7, 2015: pp. 1051-1057.
6. Fei, Zhongyang and Peters, David A., "Modal Analysis of Finite-State Dynamic Inflow for Rotary-Wing Systems," Journal of Vibration and Control. DOI: 10.1177/1077546315588396, Feb. 2016.
7. Peters, David A., Modarres, Ramin, Howard, Andrew B, and Rahming, Benjamin, "A Third Approximation to Glauert's Momentum Theory," *AHS Journal*, Vol. 61, No. 4, October 2016.
8. Modarres, Ramin and Peters, David A., "Optimum Blade Loading for a Powered Rotor in Descent," Chinese Journal of Aeronautics, Vol. 29, June 2016, pp. 580-584.

Conference Papers:

1. Fei, Zhongyang and Peters, David A. "A Rigorous Solution for Finite-State Inflow throughout the Flow-field—Including within the Wake," Proceedings of the AIAA 30th Applied Aerodynamics Conference, New Orleans, LA, June 25-28, 2012.
2. Fei, Zhongyang and Peters, David A., "Eigenvalues and Mode Shapes for the Complete Rotor Dynamic Wake Model," Proceedings of the AIAA 30th Applied Aerodynamics Conference, New Orleans, LA, June 25-28, 2012.
3. File, Chad and Peters, David A., "Blade Number Effect on Optimum Rotor Performance in Axial Flow by Dynamic Wake Theory with Improved Swirl Correction," Proceedings of the 38th European Rotorcraft Forum, Amsterdam, Sept. 4-7, 2012.

4. Modarres, Ramin and Peters, David A., "Efficient Solution of Goldstein's Equations for Propellers with Application to Rotor Induced Power Efficiency," Proceedings of the 38th European Rotorcraft Forum, Amsterdam, Sept. 4-7, 2012.

5. Fei, Zhongyang, and Peters, David A., "Inflow below the Rotor Disk for Skewed Flow by the Finite-State, Adjoint Method," Proceedings of the 38th European Rotorcraft Forum, Amsterdam, Sept. 4-7, 2012.

6. Prasad, J.V.R., Nowak, Morgan and Xin, Hong, "Finite State Inflow Models for a Co-axial Rotor in Hover," Proceedings of the 38th European Rotorcraft Forum, Amsterdam, Sept. 4-7, 2012.

7. Fei, Zhongyang and Peters, David, "Applications of Generalized Dynamic Wake Theory to the Flow in a Rotor Wake," Proceedings of the 69th Annual Forum of the American Helicopter Society, Phoenix, Arizona, May 20-24, 2013.

8. Peters, David. A. and Chugani, Jesse, "Dynamic Wake Solutions for Rotors Transitioning Between Powered and Windmill Braking Modes," Proceedings of the 69th Annual Forum of the American Helicopter Society, Phoenix, AZ, May 21-23, 2013, Paper 22.

9. Modarres, Ramin and Peters, David. A., "Optimum Performance of an Actuator Disk by a Compact Momentum Theory Including Swirl," Proceedings of the 69th Annual Forum of the American Helicopter Society, Phoenix, AZ, May 21-23, 2013, Paper 47.

10. Fei, Zhongyang and Peters, David. A., "Accurate Computation of Flow Below the Rotor Disk by a Finite-State Method," Proceedings of the 31st AIAA Applied Aero Conference, San Diego, CA, June 24-27, 2013.

11. Nowak, Morgan, Prasad, J.V.R., Xin, Hong and Peters, David, "A Potential Flow Model for Coaxial Rotors in Forward Flight," Proceedings of the 39th European Rotorcraft Forum, Moscow, Russia, Sept. 3-6, 2013.

12. Nowak, Morgan, Fei, Zhongyang, Peters, David, and Prasad, J.V.R., "Improved Finite-State Inflow Convergence through Use of a Blended Model," Proceedings of the Fifth Decennial AHS Aeromechanics Specialists' Conference, San Francisco, California, January 22-24, 2014.

13. File, Chad L. and Peters, David A., "Induced-Power Efficiency in Axial and Skewed Flow for Finite-Bladed Lifting Rotors," Proceedings of the Fifth Decennial AHS Aeromechanics Specialists' Conference, San Francisco, California, January 22 24, 2014.

14. Peters, David A., Modarres, Ramin, Howard, Andrew B, and Rahming, Benjamin, "Solution of Glauert's Contraction/Expansion Equations for Wind Turbines and Powered Rotors with Swirl," Proceedings of the 70th Annual Forum of the American Helicopter Society, Montreal, Canada, May 20-22, 2014.

15. Jianzhe, Huang, Nowak, Morgan, Peters, David, Prasad, J.V.R., "Converged Velocity Field for Rotors by a Blended Potential Flow Method," Proceedings of the 70th Annual Forum of the American Helicopter Society, Montreal, Canada, May 20-22, 2014.

16. Nowak, Morgan, Prasad, J.V.R., Xin, Hong, and Peters, David A., "Development of a Finite-State Model for a Co-axial Rotor in Forward Flight," Proceedings of the 70th Annual Forum of the American Helicopter Society, Montreal, Canada, May 20-22, 2014.
17. Peters, David A. and Huang, Jianzhe, "Real-Time Solutions of Nonlinear Potential Flow Equations for Lifting Rotors," Proceedings of the 5th Nonlinear Science and Complexity Conference, Xi'an, China, Aug. 4-9, 2014.
18. Patra, Sayan and Peters, David A., "Induced Power Efficiency in Edgewise Flow for Finite-Bladed Rotors.," Proceedings of the Society of Physics Student Conference, Liberty, Missouri, Nov. 7-8, 2014.
19. Kong, Y. B., Prasad, J. V. R., and He, C., "Analysis of a finite state coaxial rotor inflow model," Proceedings of the 41st European Rotorcraft Forum, Munich, Germany, Sept. 2015.
20. Modarres, Ramin, Peters, Luer, Williamn, Rahming and Peters, David A., "Closed-Form Solutions for the Optimum Rotor in Hover and Climb," Proceedings of the 72nd Annual Forum of AHS International, May 17-19, West Palm Beach, Florida, May 17-19, 2016.
21. Hong, JunSoo (Sean) and Peters, David A., "Induced Power Efficiency from Dynamic Wake Theory with Reversed Flow, Root Cut-Out, and Inflow Feedback," Proceedings of the 72nd Annual Forum of AHS International, May 17-19, West Palm Beach, Florida, May 17-19, 2016.
22. Kong, Y. B., Kim J. W., Prasad, J. V. R., and Sankar L. N., "Finite State Coaxial rotor Inflow Model Improvements via System Identification," Proceedings of the 72nd Annual Forum of AHS International, May 17-19, West Palm Beach, Florida, May 17-19, 2016.
23. Kong, Y.B., Prasad, J.V.R., Sankar L. N. and Peters, D. A., "Finite state coaxial rotor inflow model system identification using perturbation approach," Proceedings of the Asia-Australian Rotorcraft Forum, Singapore, Nov. 2016.
24. Kong, Y.B., Prasad, J.V.R. and Peters, D. A., "Development of a Finite State Dynamic Inflow Model for Coaxial Rotor using Analytical Methods," Proceedings of the 73rd Annual Forum of AHS International, Fort Worth, Texas, May 9-11, 2017.

Awards:

Faculty Technical Awards:

1. Dr. David A. Peters, American Institute of Aeronautics and Astronautics *Reed Aeronautics Award*, 2011.
2. Dr. J.V.R. Prasad, AIAA Fellow, 2012
3. Dr. David A. Peters, American Society of Mechanical Engineers *Spirit of St. Louis Medal,* 2013.
4. Dr. J.V.R. Prasad, AHS Technical Fellow, 2014.
5. Dr. David A. Peters, Inaugural Distinguished Lecturer, Union University, Jackson, TN, 2015.

Student Technical Awards:

1. Ramin Modarres, Vertical Flight Foundation Scholarship, 2015

2. Hong, JunSoon (Sean), "A Fully Nonlinear Version of the Pitt-Peters Dynamic Wake Model in Axial Flow," Second Place in National Robert Lichten Competition, 2013.
3. Yong-Boon Kong, AHS Student Design Competition (Graduate Category) 1st Place Winner, 2014.

Technology Transfer:

1. Collaborated with Dr. Hong Xin at Sikorsky Aircraft on Coaxial Rotor Inflow Models. Transferred the coaxial rotor inflow model code for use at Sikorsky.
2. Collaborated with Drs. Robert Ormiston and Mahendra Bhagwat on finite state inflow models and rotor performance optimization.
3. Collaborated with Dr. Chengjian He at ART on co-axial rotor finite state inflow modeling under an US Army SBIR.
4. Off-Axis Inflow work used at Sikorsky
5. ART took inflow models of Zhongyang Fei
6. Inflow models being put into RCAS and Flightlab

Task 1.5 (GT-8): Aerodynamic Flow Control for Rotorcraft Systems

PIs: Ari Glezer and Thomas Crittenden (Georgia Tech)

Background: Active flow control technologies offer tremendous potential for improving rotorcraft aerodynamic performance. Task 8 has focused primarily on aerodynamic flow control for alleviation of retreating blade stall (RBS) that continues to limit rotorcraft speed, lift capacity, and maneuverability. This phenomenon is transitory in nature, and involves complex interactions between unsteady 3D flow and blade structural dynamics in a rotating environment. Active flow control technologies present unique opportunities for RBS mitigation and thereby for improving the aerodynamic performance and efficiency of the rotor system where the induced aerodynamic forces can be used for structural stabilization, and to better match hover and cruise design conditions. Earlier investigations demonstrated the utility of mechanical slats and flaps for performance improvements of rotorcraft blades, but these techniques may be difficult to implement in practical applications. VLRCOE Task 8 focused on demonstration of the utility of fluidic-based transitory flow control for mitigation of dynamic stall and the resulting adverse aerodynamic loads on a dynamically pitching airfoil using impulsive, chemical-based actuation.

Research Objectives: The overall objectives of the flow control research were to investigate aerodynamic flow control methodologies and develop pulsed, combustion-based actuation (COMPACT) technology for mitigation of transitory stall on a dynamically pitching VR-12 airfoil with specific emphasis on manipulation of the aerodynamic forces and moments and its pitch stability. Pulsed actuation is effected on time scales that are an order of magnitude shorter than the characteristic convective time scale (T_{conv}) of the base flow using impulsive spanwise arrays of (momentary) actuation jets that are strategically triggered during the airfoil's pitch cycle thus minimizing the actuation power. This actuation approach was successfully explored in both low- and high-speed wind tunnel investigations at Georgia Tech and NASA Glenn, respectively. In addition, Task 8 research also investigated control strategies and actuation timing over a much broader range of reduced pitch frequencies using surrogate pulsed bleed actuation on a smaller wind tunnel model.

Accomplishments: A new modular VR-12 wind tunnel model integrated with a spanwise array of COMPACT actuators was designed and constructed. The model has a chord $c = 38$ cm that spans the full width of the tunnel's test section (nominally 91 cm). The actuator section of the model includes two spanwise banks each having 5 interchangeable COMPACT actuators which are mounted on either side of the centerline. The effectiveness of COMPACT-based aerodynamic flow control for mitigation of stall was first assessed on the static model (Re_c=875,000, $0 < \alpha < 22^o$). Phase-locked PIV measurements in the presence of stall confirmed that, similar to earlier observations on other airfoils, a single actuation pulse (using tangential jet actuation) leads to 2-D severing of the separated vorticity layer and the shedding of a large-scale stall vortex that is followed by transitory flow attachment within 1-2T_{conv} and, in the absence of additional actuation pulses, ultimate re-separation within 10-15T_{conv}.

The significant disparity between the characteristic time scales of flow attachment and subsequent separation was exploited for controlling the global aerodynamic loads and pitch stability on a dynamically pitching airfoil using strings of a small number of discrete successive actuation pulses during the pitch cycle. *Strategically-scheduled actuation pulses at key angles during the cycle have led to an increase of up to 5.6% in the cycle averaged total lift, even though the actuation is applied only over 20% of the model's span. The actuation also strongly enhances the pitch stability (lower "negative damping") that is typically associated with the occurrence of dynamic stall.* These investigations were complemented by "surrogate" controlled pulsed bleed actuation on a smaller wind tunnel (VR-7) model at reduced frequencies of up to $k = 0.5$. These investigations yielded an ideal testbed for exploring a broad range of actuation strategies for down-selecting suitable COMPACT-based actuation programs. The smaller model also provided significant insight into the flow physics that is associated with modification of the vorticity flux over the airfoil. These experiments demonstrated that pulsed actuation alters the production, accumulation, and advection of vorticity concentrations near the airfoil's surface with significant effects on the evolution, and, in particular, the timing of the dynamic stall vortex. The time-periodic changes in lift during the up- and down-stroke segments of the pitch cycle are accompanied by mitigation of sharp excursions of the pitching moment in the base flow, and in complete reversal of the "negative damping" indicating potential for improvement of the stability of flexible rotor blades. Building on these results, COMPACT-based actuation demonstrated that properly-staged pulsed actuation can lead to significant reduction in the magnitude of the transitory peak of the pitching moment $C_{M\text{-max}}$ during the cycle. While the global aerodynamic loads of the base flow over the pitching airfoil are not very sensitive to vibrations (the averaged lift, the nominal stall angle, and the pitch stability remain nearly unchanged), *the effectiveness of staged pulsed actuation appears to increase in the presence of the vibrations*. Compared to actuation during pitch only, in the presence of plunge vibrations the actuation-induced increments in cycle-averaged lift and in the peak C_L prior to dynamic stall nearly doubled, and the reduction in $C_{M\text{-max}}$ increased by nearly fourfold. On the other hand, the actuation-induced improvement in pitch stability of the pitching airfoil in the absence of actuation remained unchanged.

The COMPACT actuation technology developed under the VLRCOE program was transitioned to high-speed investigations in a parallel collaborative effort between UTRC, Sikorsky, and Georgia Tech under a NASA NRA program. COMPACT actuator designs were implemented on a larger span (~175 cm) VR-12 model and tested in dynamic pitch the NASA Glenn IRT tunnel. These tests demonstrated post-stall flow reattachment using COMPACT actuation up to $M = 0.4$ with large transitory increases in C_L. Based on the low-speed wind tunnel tests at Georgia Tech, the NASA Glenn tests demonstrated that the enhancement in lift can be realized with actuation programs utilizing only a small number of strategically-staged actuation pulses during the pitch cycle. These findings indicate that this new pulsed actuation approach can be highly effective at rotorcraft flight speeds. Based on these tests, investigations for improvements in

the performance of the actuator in low-pressure environments (owing to altitude and high-speed cross flow) have been undertaken. Vacuum chamber tests suggest that actuator performance (in terms of pressure ratio relative to the ambient) is largely unaffected at reduced pressures but may require larger spark gaps and/or increased spark energy. Next-generation actuator designs and ancillary electronics are currently under development and will be available for large-scale testing.

Students supported under the project

1. John Kearney (US): Full GRA (50% time), 2013-2016, PhD awarded May 2016, Apple, Cupertino, CA.
2. Yuehan Tan (China): Full GRA (50% time), 2014-2017, PhD anticipated May 2019.

Patents/Software Invention Disclosures

None

Publications;

Theses

1. Kearney, J. M., Aero-Effected Flight Control using Distributed Active Bleed, PhD Thesis, Georgia Institute of Technology, Spring 2015. https://smartech.gatech.edu/handle/1853/55515

Journal papers:

1. Matalanis, C., Min, B.-Y., Bowles, P., Jee, S., Wake, B., Crittenden, T., Woo, G., and Glezer, A., "Combustion-Powered Actuation for Dynamic-Stall Suppression: High-Mach Simulations and Low-Mach Experiments," *AIAA J.*, **53**, 2151-2163, 2015.
2. Kearney, J. M., and Glezer, A., "Aerodynamic Control using Distributed Active Bleed," *submitted to AIAA Journal.*

Conference Papers:

1. Kearney, J., and Glezer, A., "Aerodynamic Control Using Distributed Bleed," AIAA Paper 2012-3246, 6th AIAA Flow Control Conf., New Orleans, LA, June 2012.
2. Kearney, J., and Glezer, A., "Aero-Effected Control of a Pitching Airfoil by Bleed Actuation," AIAA Paper 2013-2519, 31st AIAA Fluid Dynamics Conf., San Diego, CA, June 2013.
3. Kearney, J., and Glezer, A., "Aerodynamic Control of a Pitching Airfoil by Active Bleed," AIAA Paper 2045, 32nd AIAA Applied Aerodynamics Conf. Atlanta, GA, June 2014.
4. Kearney, J. M., and Glezer, A., "Aerodynamic Control by Regulation of Surface Vorticity Flux using Active Bleed," 10th International ERCOFTAC

Symposium on Engineering Turbulence Modelling and Measurements, Marbella, Spain, September, 2014.

5. Tan, Y., Crittenden, T., and Glezer, A., "Aerodynamic Control of a Dynamically Pitching VR-12 Airfoil Using Discrete Pulsed Actuation," AIAA Paper 2016-0321, 54th AIAA Aerospace Sciences Mtg., San Diego, CA, January 2016.

6. Kearney, J., and Glezer, A., "Aerodynamic control by vorticity transport modification using distributed active bleed," IACAS 2016 56th Israel Annual Conference on Aerospace Sciences, 2016.

Awards
None

Technical Transfer

The COMPACT actuation technology developed under the VLRCOE program was transitioned from low-speed to high-speed investigations (both utilizing VR-12 airfoil models with the same chord size) in a parallel effort with UTRC and Sikorsky under a NASA NRA program. The high-speed tests clearly showed that COMPACT actuation can mitigate the adverse effects of VR-12 stall up to $M = 0.4$. Actuation on the static airfoil yielded post-stall lift increments of 50% ($M = 0.3$) and 25% ($M = 0.4$), and cycle-averaged lift increment during dynamic pitch of up to 11% at $M = 0.4$. The COMPACT research partnership with UTRC and Sikorsky is continuing, and plans for large-scale, rotating blade test are under development.

Task 1.6A (GT-10A): Experimental Aerodynamic-Dynamic Interaction of Bluff Bodies

PI: Narayanan M. Komerath (Georgia Tech)

Background: Very little was known about predicting the aerodynamic loads on a bluff body at arbitrary attitude in a flow. The basic research here was driven mostly by the problem of developing efficient and reliable alternatives to individual flight testing for every case of a flight vehicle combined with a particular slung load, in order to certify the safe flight envelope. Airload mapping in principle requires infinite combinations of attitudes and combinations. Fine resolution is needed over small attitude variations. A set of 6 generic shapes was initially chosen.

Research Objectives: The first objective was to capture and understand aerodynamic load maps of bluff bodies, towards generalized predictions. The second objective was to predict divergence speeds of various objects given rigid tethers.

Accomplishments: The Continuous Rotation method of mapping 6-DOF airloads invented out of necessity in this Task, converted the static measurement to a periodic problem. Highly resolve aerodynamic load maps of arbitrary shapes at arbitrary orientations, were generated as closed-form, truncated Fourier series. Swing tests with measured inertia and bearing friction revealed dynamic behavior.
In Year 1, we showed why unsteady wall effects would amplify oscillations of an object suspended in a freestream. Aerodynamic load maps were developed for over 50 different models spanning canonical shapes as well as practical configurations. The knowledge base accumulated from these tests enables interpolated prediction for other shapes. *We submit that this is a fundamental breakthrough in bluff-body aerodynamics.*
     The above enabled a bottom-up approach to predicting the load dynamics and divergence speed. Experience in the community shows that when the slung load is less than a third of the vehicle gross weight, the effect of the load dynamics on the vehicle dynamics is negligible. Human-piloted helicopters can rarely fly fast with an external payload that is greater then 33% of its gross weight. Thus the load dynamics could be predicted independently of the vehicle dynamics, in other words using a MatLab/Simulink computation rather than using a huge Vehicle Dynamics code. Diagnostic experiments debunked wild claims and confirmed common sense based on Reduced Frequency that quasi-steady, slow-rotation data are perfectly adequate for the purpose. Each model exhibits a distinct divergence speed. At AHS Forum 2015 we showed 2 important results: that small errors in the loads or resolution of loads data, had less than a proportional effect on the eventual divergence speed. Further, changes in initial perturbation might affect amplification history, but had little effect on eventual divergence speed. A UAV quadrotor flying near the divergence speed, roll amplification due to sudden gusts could be robustly damped out by vehicle flight

control. In Year 5, we performed two "final exam cases" on the Engine Canister and the Ribbon Bridge. We showed a transparent procedure whereby uncertainty in divergence speed and overall dynamic behavior, was systematically reduced. In both cases were able to capture intermediate spikes in maximum, roll amplitude, and explain why each test was stopped because of the maximum trailing angle excursions. From the above results, we submit that we have shown how to predict the divergence speed, and the intermediate dynamics, of practical slung load configurations swiftly, and with rapidly-increasing certainty, so that certification of new, arbitrary shapes can be done in an efficient and reliable manner. This was the original problem set in 2008.

Students
1. Nandeesh Hiremath (MSAE, 2014; PhD program, GIT AE)
2. Dhwanil Shukla (MSAE, 2015; PhD program, GIT AE)
3. Ranjit Mantri (MSAE 2011, US Govt)
4. Alexander Forbes (MSAE2014, GTRI)
5. Sorin Pirau (BSAE 2012; MSAE 2014, Pratt & Whitney)
6. Nicholas Motahari (MSAE 2016, Pratt & Whitney)

7.- 47: BSAE project participants:

Brandon Liberi, (BSAE 2014; Raytheon, AZ) David Miculescu, Colin Swearingen, Roger Campbell, Siddhant Agarwal, Somil Shah, Ponthus Pryonneau, Akshay Bakane, Gautam Kumar, William Kelley, Ishan Desai, Jeremiah Robertson, Avani Gupta, Ari Videlefski, Jong Lee, Nam Kim, Yuanxin Shen, Nicholas Zambetti, Eric Stoker-Spirt, Max Germain, Victor Heulme, Kijjakarn Pradityukrit, Thomas Rainey, Jordan Trout, Chukwudera Mojekwu, David Babb, Thomas Kim, Daven Patel, Arvin Ajmani, Guilherme Engler, Lucas Parra, Kim Anh Phan, Bryan Liberman, Ayush Jha, Jackson Merckl, Joseph Robinson, Franklin D'Turbeville, Emily Hale, Taylor Sparacello, Ayush Jha, Arun Palaniappan.

Patents/Software Invention Disclosures
1. Continuous Rotation Method for Aerodynamic Loads. Invention Disclosure, 2015.
2. SLAD. Invention Disclosure, 2016.

<u>Faculty Technical Awards</u>
N. Komerath, AIAA (2016) and ASEE(2015) John Leland Atwood Award

<u>Student Technical Awards</u>
1. Sumant Sharma (2011) PURA
2. Sumant Shama (2012) Southern Division Winner, Lichten Award Competition, AHS.
3. Sumant Sharma (2012) Vertical Flight Foundation Scholarship
4. Sumant Sharma (2013) PURA, Brandon Liberi (2014) PURA
5. Sorin Pirau (2014) Vertical Flight Foundation Scholarship
6. Brandon Liberi (2014) Vertical Flight Foundation Scholarship

7. Brandon Liberi, 2014: Outstanding Undergraduate Researcher, COE, Georgia Tech
8. Avani Gupta (2014) PURA, Jackson Merkl (2015) PURA
9. Jackson Merkl, Vertical Flight Foundation Fellowship
10. Jermemiah Robertson, 2016, Fulbright Scholarship finalist
11. Nicholas Motahari and Nandeesh Hiremath (2015), Georgia Graduate Research Symposium, Columbus State University. Best poster presentation.
12. Nandeesh Hiremath (2017) Vertical Flight Foundation Scholarship

Publications

Journals:
1. Komerath, N., Hiremath, N., Closed Rectangular Prisms in Yaw. Aerodynamics of Arbitrary Shapes, Vol.4. ASIN: B074Y8STJS, SCV, Nov. 2017.
2. Komerath, N., Raghav, V., Hiremath, N., Aerodynamic Loads on Arbitrary Shapes. SCV, ISBN 978-0-9962283-9-8, Oct. 2016.
3. Komerath, N., Hiremath, N., Closed Circular Cylinders in Yaw. Aerodynamics of Arbitrary Shapes, Vol.2..SCV, ISBN 978-0-9962283-8-1, Nov. 2016.
4. Sharma, S., Komerath, N.M et al, Wall Effect On Fluid-Structure Interactions Of A Tethered Bluff Body. Physics Letters A, Vol. 377, Issues 34–36, 1 Nov. 2013, p.2079-2082.
5. Pirau, S., Liberi, B., Barbely, N., Komerath, N., Aerodynamic Load Maps of Bluff Bodies: Measurement and Diagnostics. J. Mechanical Sciences and Technology, Springer, 2016.

Conference Papers:
1. Sharma, S., Komerath, N.M., et al, Aerodynamic Instability Modes For a Load Slung From a Helicopter. Peer-reviewed paper IMECE2012-85693, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition*, Houston, TX. November 2012.
2. Liberi, B., Pirau, S., Raghav, V.S, Komerath, N.M., Determination of Slung Load Divergence Speed. Peer-reviewed paper IMECE2014-38260, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition*, Montreal, Nov. 2014.
3. Pirau, S., Liberi, B., Forbes, A., Raghav, V.S, Komerath, N.M., Efficient Airload Determination for Slung Loads. Peer-reviewed paper ASME IMECE2014-37638, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* Montreal, November 2014.
4. Liberi, B., Ton, C., Komerath, N.M., Divergence Speed Prediction for Practical Slung Load Shapes. Peer-reviewed paper, *Proceedings of the ASME-JSME-KSME Joint Fluids Engineering Conference*, Seoul, Korea, July 2015.
5. Pirau, S., Liberi, B., Barbely, N., Komerath, N., Generalizing Prediction of the Aerodynamic Load Maps of Bluff Bodies. Peer-reviewed paper 2015-15542, *Proceedings of the ASME-JSME-KSME Joint Fluids Engineering Conference,* Seoul, Korea, July 2015.

6. Liberi, B., Pradityukrit, K., Komerath, N., Slung Load Divergence Speed Predictions for Vehicle Shapes. Peer-reviewed paper 15ATC-0214, SAE AeroTech, Seattle, WA, September 2015.

7. Motahari, N., D'Turbeville, F., Komerath, N., Airload Maps of Vehicle Shapes at Arbitrary Attitude. Peer-reviewed paper 15ATC-0198, SAE AeroTech Conference, Seattle,WA, September 2015.

8. Shukla, D., Hiremath, N., Motahari, N., Komerath, N., Genesis of the Airload Variations on Cylinders of Small Aspect Ratios. Peer-reviewed paper IMECE2015-52636, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* Houston, November 2015.

9. Motahari, N., Hiremath, N., Shukla, D., Liberi, B., Thorrell, N., Komerath, N., Generalized Airload Prediction for Bluff Bodies. Peer-reviewed paper IMECE2015-52570, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* Houston, November 2015.

10. Nicholas Motahari, Nandeesh Hiremath, Narayanan Komerath, Aerodynamic Load Maps of Bluff-Body Combinations in Incompressible Flow. Peer-reviewed paper FEDSM2016-7683, *Proceedings of the ASME Fluids Engineering Conference*, Washington July 2016.

11. Shukla, D., Hiremath, N., Komerath, N., A Cycloidal Rotor and Airship System for On-Demand Hypercommuting. Peer-reviewed paper, *Proceedings of the SAE Aerospace Systems Conference*, Hartford, CT, Sep. 2016.

12. Motahari, N., Shukla, D., Hiremath, N., Komerath, N., Aerodynamic Load Mapping of Bluff Bodies: An Update and Summary. Peer-reviewed paper IMECE 2016-6105, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition*, Phoenix, AZ, Nov. 2016.

13. Motahari, N., Kim, T., Shukla, D., Hiremath, N., Komerath, N., Divergence Prediction for Practical Helicopter Slung Loads. Peer-reviewed paper IMECE 2016-66119, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition*, Phoenix, AZ, Nov. 2016.

14. Forbes, A., Pirau, S., Liberi, B., Raghav, V.S., Komerath, N.M., Testing-Based Approach to Determining the Divergence Speed of Slung Loads. *Proceedings of the AHS 69th Forum*, Montreal, May 2014.

15. Liberi, B., Pirau, S., Komerath, N., Ton, C., Effects of Uncertainty on Slung Load Divergence Speed Determination. *Proceedings of the AHS 71st Annual Forum*, Virginia Beach, May 2015.

16. Motahari, N., Hiremath, N., "Divergence Speed Determination of Slung Loads". *Proceedings of the Georgia Graduate Research Symposium*, Columbus State University, Columbus, GA, November 2015.

17. Shukla, D., Thorell, Aerial Commuter Architecture Using Slung Loads. *Proceedings of the AHS Forum 72*, West Palm Beach, FL, May 2016.

18. Motahari, N., Hiremath, N., Shukla, D., Komerath, N., Generalized Approach for Slung Load Aerodynamics. *Proceedings of the AHS Forum 72*, West Palm Beach, FL, May 2016.

19. Motahari, N., Hiremath, N., Shukla, D., Komerath, N., Towards Generalized Certification of Slung Load Flight Envelopes. *Proceedings of the AHS Forum 72*, West Palm Beach, FL, May 2016.

20. Komerath, N., Shukla, D., Robinson, J., Jha, A., Palaniappan, A., Aerodynamic Loads on Arbitrary Configurations: Measurements, Computations and Geometric Modeling. Peer-reviewed paper 2017-01-2162, *Proceedings of the SAE Aerotech Conference*, Ft. Worth, TX, September 2017.
21. Hiremath, N., Shukla, D., Hale, E., Sparacello, T., Komerath, N., Slung Load Amplification Detector. Peer-Reviewed paper IMECE2017-70252, *Proceedings of the ASME 2009 International Mechanical Engineering Conference & Exposition IMECE2017*, November 3-9, 2017, Tampa, USA

Technology Transfer: In 2016-17 the Continuous Rotation method was used in an ART SBIR project under a Navy prime contract to define the aeromechanics of a towed body and a complex UAV helicopter model. Comparison with true *a priori* computational predictions showed excellent success in predicting unexpected physical features. Jan Goericke, ART, jan@flightlab.com

Task 1.6B (GT-10B): Computational Aerodynamic-Dynamic Interaction of Bluff Bodies

PIs: Marilyn J. Smith (Georgia Tech)

Background: Many applications require better understanding of the unsteady aeromechanics of bodies of complex shape. Examples in rotorcraft technology are those of the coupled aeromechanics of arbitrary-shaped loads slung below a fast-moving rotorcraft or delivered to the deck of a rolling ship on a windy day. Other examples include aerodynamic deceleration for planetary entry, store separation from aircraft, precision airdrop, and towed aquatic vehicles. The basic research problem is that these flows involve unsteady fixed-point flow separation, transition and separation over curved surfaces, interaction between shear layers and vortices, interaction between aerodynamics and body dynamics, and the resonant amplification of multi-degree-of-freedom dynamics throughout the speed regime. The high-fidelity computational efforts include the potential to advance the understanding and prediction of the aerodynamics/dynamics interaction of a broad canonical range of bluff body shapes for these applications.

Research Objectives: The primary objective is to capture the spectrum of coupled unsteady aerodynamic-dynamic behavior encountered by a subset of canonical shapes relevant to rotorcraft. The second objective is to identify the basic aerodynamic phenomena associated with the dynamic behavior, such as the mode of shedding and/or separation. From these characterizations, empirical behavior and/or algorithms to describe the aerodynamic-dynamic interactions will be developed to permit application in the development of flight operations and/or simulations or active/passive controls of bluff body aerodynamics. The successful completion of these objectives will provide guidance to the rotorcraft community to develop techniques other than reliance on flight testing for future bluff body studies.

Accomplishments: This effort was originally a teamed effort with both a computational and experimental approach. The computational effort was designed to provide high-fidelity analysis of these bluff bodies, assessing and improving the current state of the art in computational analysis of these bodies. Further, provided with design of the wind tunnel models, mounts and test conditions, the computational analyses would provide feedback to a parallel experimental effort. These computations were obtained *a priori* to experimental correlation, either before or after the actual tests, based on when the information was provided to the computational team, and used to guide, confirm, and/or augment wind tunnel results.

   The computational approach utilizes the NASA-developed unstructured CFD code FUN3D and structured code, OVERFLOW, adapted to improve the capture of the turbulent features of large-amplitude bluff-body aeromechanics and provide high-fidelity numerical experiments that can augment or replace experimental endeavors, depending on the engineering need. For these highly unsteady flows, feature-based grid adaption is applied to the simulation, which improves grid quality in the turbulent wake of a bluff body without significant increase in the computational costs. Large eddy simulation (LES)-based

turbulence closures can dramatically improve the ability to capture the turbulent wake structure, as well as reattachment and separation, thus providing more accurate load prediction.

Based on results in the first two years of this project, the computational approach has been expanded to include the detailed analysis and assessment of a *physics-based* reduced-order approach to replicate the dynamic behavior of bluff bodies. The key to this reduced-order modeling approach is the ability to use only quasi-steady (static) behavior of aerodynamic bluff bodies, augmenting the behavior with unsteady fluid dynamics theory. This permits the use of computational and experimental data, and does not restrict the method to response surface "black boxes" that require significant unsteady evaluation, and do not lend themselves to adaptation of new configurations.

The computational progress during the first two years was focused on the analysis of the physics of three-dimensional rectangular and cylinder configurations, correlating with both Georgia Tech and external experimental data, where available. *A priori* computational efforts, performed prior to access of experimental data, successfully isolated several issues with the parallel wind tunnel campaign, in particular for cylindrical configurations. The computational analyses resulted in a new set of wind tunnel models and mount being developed in 2013 and retested. After the new GT cylinder wind tunnel models (2013 tests) were measured in detail by the Army, discrepancies in the wind tunnel model from the canonical configuration were identified; a high-fidelity sensitivity analysis was completed and provided to the Army in mid 2014. Issues with the lack of suitable correlation data from the experimental track of this project has led to new cooperation and collaborations with the US Army (Natick), Germany (DLR), the University of Maryland (UMD), the UK (ARA), and Israel (Technion) to obtain the high-quality data necessary for the computational approach, including data at higher, more realistic Reynolds numbers than previously available in this project.

The inability to obtain gimbal friction from the wind tunnel experiments in late 2012 led to the development of an advanced six degree-of-freedom simulation code with reduced order modeling (ROM). The highly-accurate physics-based ROM approach, based on Peters' unified aerodynamics, Theodorsen, and ONERA dynamic stall theories, is extensible to flight conditions and new configurations. It currently requires quasi-steady aerodynamics from either computations or experiments. Analysis using computational, flight test and wind tunnel data indicates it provides accurate prediction of both a tethered load stable location and its unstable behavior. To date on data available, the validity of the model extension to other speeds, Reynolds numbers, and aspect ratios has been successfully demonstrated. "Virtual wind tunnel" tests show that the divergence speed under operating conditions is unlikely to be sufficient for certification as the unsteady wind/turbulence, as well as the vehicle motion is necessary. Thus, for certification purposes, sensitivity studies and a range of divergence speeds under operational constraints are needed for practical implementation, which are continuing with the Aviation Engineering Division (AED) and Natick Army engineers. This also illustrates limitations in using a wind tunnel test for divergence speed predictions beyond the issues of interference effects and

model scales, a finding confirmed by others in the field. GTABB cost reductions with no loss in accuracy have yielded a near-real time capability, and it has been implemented in Flightlab by the US Army (AED) and in Simulink (GT, Robotics Lab). This ROM has been compiled into a library, known as the **G**eorgia **T**ech **A**erodynamics of **B**luff **B**odies (GTABB). It has been applied in GT VLRCOE Task 16 for control development of underslung loads for UAVs.   Through leveraging of graduate and undergraduate students for class and GT Presidential Undergraduate Research Awards (PURA), many additional enhancements to GTABB include: GUIs developed with Army inputs; dynamic long tethers (currently not real time); no-gimbal option (tether windup), and additional flight test validation. Using CIFER, the frequency domain results concretely demonstrate that a key frequency needed for accurate instability analysis in real atmospheric conditions was identified, and the missing aerodynamic frequencies due to the near body unsteady aerodynamics model has been identified for model enhancement. In 2015-2017, GTABB has been successfully extended for design of highly maneuverable vehicles, in particular for control laws, which have been demonstrated in subsequent vehicle flight tests. The US Army is evaluating GTABB for use in modeling and simulation applications.

Major strides in understanding the physics of the aerodynamic-dynamic interactions have also been made using CFD and correlated with extant experimental data (UK, UMD, Technion, US Army). In 2011 (published in 2012), it was postulated based on initial understanding of the physical behavior of these bluff (and aerodynamic) bodies, that formal quasi-steady training data from CFD or wind tunnel tests may not be necessary for the modeling and assessment of more complex bodies. In 2015-2017, this hypothesis was confirmed, resulting in a new complex model preprocessor for GTABB known as COMPASS (Complex Aerodynamic Shape Simulation. This effort continues with a follow-on project with the US Army (Natick).

A source-based CFD methodology to model porous materials including both boundary conditions and turbulence corrections was begun and will continue as collaborative experimental data is obtained. Continued validation and expansion of GTABB, including uncertainty quantification, to new configurations and higher Technology Readiness Levels (TRLs) continues with the US Army (AED, AFDD, Natick). Helios-based CFD approaches for new, advanced sling loads concepts are continuing through a new joint Army-GT CREATE-AV project.

Students and Researchers supported under the project:

1. Dan Prosser (USA): supported 50% time from 7/2012 - 9/2014; 100% time from 10/2014 - 6/2015, PhD awarded August 2015, Aeronautical Engineer, US Navy, Patuxent River, MD.   PhD thesis is on this effort.
2. Nicholson Koukpaizan (Benin): supported 25% time in 2017 to maintain and extend GTABB, currently pursuing PhD.
3. Amanda Grubb (USA): supported 50% time in Fall 2015 to perform CFD computations, currently pursuing PhD.
4. Aaron Wilks (USA): supported 100% time in Fall 2017, currently pursuing MS (and potentially his PhD) at Georgia Tech. Continued funding under CREATE-AV project.

5. Juan Pablo Afman (USA) supported 25% from 9/2016 - 9/2017 to perform frequency domain analysis and control law design; currently pursuing PhD in Robotics at Georgia Tech.
6. Omid Nabipour (USA): Master's Project, two semesters, Spring- Summer 2015, course credit only, MSAE awarded August 2015, Aeronautical Engineer, US Navy, China Lake, CA.
7. Albane Lorieau (France): Master's Project, two semesters, Summer- Fall 2015, course credit only, MSAE awarded December 2015, Aeronautical Engineer, SAFRAN, France.
8. James Clinton (USA): undergraduate, summer intern, class credit and Presidential Undergraduate Research Award (PURA), 2015-2016. Started MSAE degree in 2017.
9. Avani Gupta (India): undergraduate, summer intern, class credit and Presidential Undergraduate Research Award (PURA), 2015-2016. Supported 25% in Spring 2016 before moving to a new group.
10. Sivva Mova (USA): undergraduate, class credit and Presidential Undergraduate Research Award (PURA), 2015-2016. Returning to pursue MSAE in group in 2018.
11. Terry Ma (USA): undergraduate, class credit, 2 semesters, 2015.
12. Franklin Turbeville (USA): undergraduate, class credit, 1 semester, 2015.

Patents/Software Invention Disclosures:

Software Disclosures for GTABB (Prosser, Smith, Koukpaizan) and COMPASS (Prosser, Smith, Koukpaizan, Wilks) in 2017 to facilitate transition to DoD and industry.

Publications:

Theses

1. D. T. Prosser. Advanced Computational Techniques for Unsteady Aerodynamic–Dynamic Interactions of Bluff Bodies. PhD thesis, Georgia Institute of Technology, Atlanta, Georgia, 2015. https://smartech.gatech.edu/handle/1853/53899.

Journal Papers

1. D. Prosser and M. J. Smith. Aerodynamics of Finite Bluff Bodies. *Journal of Fluid Mechanic*s, 799(6):1–16, 2016.
2. D. Prosser and M. J. Smith. A Physics-Based Reduced-Order Aerodynamics Model for Bluff Bodies in Unsteady, Arbitrary Motion. *Journal of the American Helicopter Society*, 60(3):1–15, 2015.
3. S. Sharma, V. Raghav, N. M. Komerath, and M. J. Smith. Wall Effect on Fluid-Structure Interactions of a Tethered Bluff Body. *Physics Letter A*, 377(34-36):2079–2082, 2013.
4. D. Prosser and M. J. Smith. Flow Characteristics Around Rectangular Bluff Bodies at Angle of Attack. *Physics Letters A*, 376(45):3204–3207, 2012.

Conference Papers:

1. K. Bergeron, A. Grubb, and M. J. Smith. Quasi-static and Prescribed Motion Simulations for Helicopter Sling Loads. Kissimmee, FL, January 8–12 2018. To be presented at the AIAA Science and Technology Forum and Exposition 2018, CREATE-AV Special Session.

2. N. K. Koukpaizan, A. Grubb, and M. J. Smith. Reduced-Order Modeling of Complex Aerodynamic Geometries Using Canonical Shapes, Kissimmee, FL, January 8–12 2018. To be presented to the AIAA Science and Technology Forum and Exposition 2018.

3. J. P. Afman, N. K. Koukpaizan, A. Grubb, and M. J. Smith. An Enhanced Prediction Methodology for Rapid Performance and Control Design of Highly Maneuverable UAVs. Proceedings of the 43rd European Rotorcraft Forum, Milan, IT, September 12–15 2017.

4. N.K. Koukpaizan, J. Movva, M. Butori, and M. J. Smith. Accurate Real-Time Extensible Simulations of Dynamic Bodies. Proceedings of the American Helicopter Society 73rd Annual Forum, Ft. Worth, TX, May 9-11 2017.

5. Lorieau and M. J. Smith. Towards Certification of the Modeling of Complex Systems: Slung Loads. Proceedings of the AHS Development, Affordability and Qualification of Complex Systems Specialists Meeting, Huntsville, AL, Feb. 9–11 2016.

6. O. Nabipour, J. Clinton, T. Ma, D. Prosser, and M. J. Smith. Aerodynamic Influences on the Modeling and Simulation of Instabilities on Dynamic Tethered Loads. AIAA Science and Technology Forum and Exposition, AIAA-2016-2141, San Diego, CA, January 2016.

7. D. Prosser and M. J. Smith. Physics-Based Aerodynamic Simulation Models Suitable for Dynamic Behavior of Complex Bluff Body Configurations. Proceedings of the American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May 2015.

8. D. Prosser and M. J. Smith. Aerodynamics of Finite Cylinders in Quasi-Steady Flow. AIAA 53rd Aerospace Sciences Meeting, AIAA-2015-1931, Orlando, FL, January 2015.

9. D. Prosser and M. J. Smith. A Novel, High Fidelity 6-DoF Simulation Model for Tethered Load Dynamics. Proceedings of the 70th American Helicopter Society Forum, Montreal, Canada, May 20–22 2014.

10. D. Prosser and M. J. Smith. Three-Dimensional Bluff Body Aerody- namics and its Importance for Helicopter Sling Loads. Proceedings of the 40th European Rotorcraft Forum, Southampton, UK, Sept. 2–4 2014.

11. D. Prosser and M. J. Smith. Navier-Stokes-Based Dynamic Simulations of Sling Loads. 54th AIAA/AHS/ASME Structural Dynamics and Materials Conference, AIAA-2013-1922, Boston, MA, April 2013.

12. S. Sharma, N. Komerath, and M. J. Smith. Efficient Modeling of Dynamic Blockage Effects for Unsteady Wind Tunnel Testing. Proceedings of the American Helicopter Society 69th Annual Forum, Phoenix, AZ, May 21–23 2013.

13. S. Sharma, N. Komerath, M. J. Smith, and V. Raghav. Aerodynamic

Instability Modes for a Load Slung from a Helicopter. Proceedings of ASME 2012 International Mechanical Engineering Congress & Exposition IMECE 2012, IMECE2012-86446, Houston, Texas, November 11–14, 2012. ASME.

14. R. Mantri, V. Raghav, N. Komerath, and M. J. Smith. Stability Predic- tion of Sling Load Dynamics Using Wind Tunnel Models. Proceedings of the 67th American Helicopter Society Annual Forum, Virginia Beach, Virginia, May 2–5 2011.

15. R. Mantri, V. Raghav, N. Komerath, and M. J. Smith. Study of Factors Driving Pitch, Roll, and Yaw Coupling in Bluff Body Aerodynamics. AIAA 41st Fluid Dynamics Conference and Exhibit, AIAA-2011-3445, Honolulu, Hawaii, June 27–30 2011.

Awards:

Team Technical Awards:

1. Best Paper, Modeling and Simulation, American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May, 2015.
2. Best Paper for Systems Integration Division and Gessow AHS Forum best paper finalist, American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May, 2015.
3. Research featured in AIAA Aerospace America, "Bearing Heavy Loads", 2014.

Faculty Technical Awards:

1. Marilyn Smith, Agusta-Westland International Fellowship Award (AHS, HART-II Workshop), 2012
2. Marilyn Smith, Agusta-Westland International Fellowship Award (AHS, US/France PA), 2014
3. Marilyn Smith, American Helicopter Society Technical Fellow, 2015
4. Marilyn Smith, AIAA Fellow, 2015
5. Marilyn Smith, NASA Group Achievement Award (FUN3D Development Team, rotorcraft contributions), 2017 (with Hodara, Lind and Jones)
6. Marilyn Smith, Invited seminars at several places 2011-2017

Student Technical Awards:

(See Task 3 for Amanda Grubb Awards)

1. Daniel Prosser, PhD Scholarship, Vertical Flight Foundation (AHS), 2013.
2. Daniel Prosser, Georgia Tech Presidential Fellow, 2012-2015.
3. Daniel Prosser, ARCS Fellow, 2013-2014.
4. Daniel Prosser, ARCS Fellow, 2014-2015.
5. Daniel Prosser, *Aviation Week*, Twenty 20s, 2013.
6. Daniel Prosser, 2nd Place 12th Overset Grid Symposium Poster Competition.
7. Daniel Prosser, Best Paper, Modeling and Simulation, American Helicopter Society 71st Annual Forum, Virginia Beach, VA, May, 2015.
8. Daniel Prosser, Best Paper for Systems Integration Division and Gessow AHS Forum best paper finalist, American Helicopter Society 71st Annual

Forum, Virginia Beach, VA, May, 2015.

9. Siva Movva, President's Undergraduate Research Award (PURA), Spring 2016.
10. James Clinton, President's Undergraduate Research Award (PURA), Fall 2015 and Spring 2016.
11. Avani Gupta, President's Undergraduate Research Award (PURA), Fall 2016.

Technology Transfer:

- Sling Loads reduced order model (**G**eorgia **T**ech **A**erodynamics of **B**luff **B**odies, GTABB) and preprocessor for complex shape development (**Comp**lex **A**erodynamic **S**hape **S**imulation) provided to US Army (AED, Natick), US Navy (Natick), Penn State University (PSU), Carleton University (Canada), Sikorsky, as well as small businesses. Several additional requests are pending.

- Computational capabilities (FUN3D within Helios) under further assessment and transfer to US Army (Natick) for use in Army sling load applications.

- Efforts underway in concert with AED to develop certification requirements for sling loads using GTABB and COMPASS.

- GTABB is being assessed for development of control strategies for airfoils and vehicles encountering gusts (as part of AVT 282 Technical Team).

- This effort has involved collaborations with US Army (Thompson, Moulton, and Brackbill, AED; Ciccolani and Tischler, AFDD; and Bergeron, Natick), Germany (DLR), Jewel Barlow at the University of Maryland (UMD), Doug Greenwell at ARA (UK), and

Task 1.7 (GT-11): Multifunctional Sensors for Loads Monitoring and Structural Diagnostics

PIs: Massimo Ruzzene (Georgia Tech) and Carlos E. S. Cesnik (Univ of Michigan)

Background: Fatigue, wear and damage limit structural life and are common reasons for replacement of critical airframe components (including rotor blades). Damage and usage monitoring are essential to the development of timely and cost effective maintenance of rotorcraft. It is estimated that 8% of any rotary wing fleet should be overhauled each year to maintain maximum readiness and safety. Effective monitoring of structural hot spots can substantially reduce inspection and maintenance costs and extend the operational life of an aircraft. Such monitoring relies on efficient, multifunctional sensors for loads monitoring and structural integrity estimation, which are key to development of Condition Based Maintenance (CBM) processes.

Research Objectives: The research in this task contributes to the implementation of CBM through the design, analysis, manufacturing, and testing of multifunctional sensors for Structural Health Monitoring (SHM) using active interrogation and passive monitoring of structural integrity, as well as for fatigue life estimation through strain monitoring. Novel power-efficient, long-range and active guided wave-based SHM system were developed for the inspection of rotorcraft structural components. The research sought the integration of tailored Composite Long-range Variable-direction Emitting Radar (CLoVER) and Frequency Steerable Acoustic Transducer (FSAT) transducers.

The basic research issues that were addressed to achieve the project objectives include the improved fundamental understanding of wave propagation characteristics of metallic and composite plates as representative of rotorcraft structural panels. In addition, a concept for strain sensing using electrode patterning has been explored in depth and investigated through theoretical and experimental studies. Fundamental theoretical foundations and numerical formulations have guided the application of these concepts to a broad variety of structural components in order to ultimately support a CBM approach to rotorcraft structural health.

Accomplishments: The work conducted during this project has focused on (i) extensive modeling and simulation of wave generation, propagation, and interaction with various types of structural damage through further development of the Local Interaction Simulation Approach (LISA) method, (ii) extensive testing of FSAT capabilities in radiation mode with concept extension to composites, (iii) development and testing of the *refined* integrated CLoVER/FSAT transducer in radiation mode, (iv) testing of FSAT performance as a standalone damage detection device through pulse-echo operations both on aluminum and composites, and (v) framework development and in depth investigation of suitable fabrication pattern for the AWR as a Micro Electro-Mechanical System (MEMS).

The UM-LISA framework was developed as an efficient way to model guided wave generation, propagation and interaction with damage in both

metallic and composite structures. Its implementation using the Compute Unified Design Architecture (CUDA) allowed for the massively parallel GPU-based implementation code that achieved orders of magnitude higher computational efficiency than the original one and commercial FEM. The improved LISA framework integrated seamlessly with commercial preprocessors for structure geometry generation, discretization, and material allocation, which facilitates the modeling of complex structures. A hybrid local FEM/global LISA and a direct piezo-coupled LISA approaches were developed as new methodologies to accurately capture the actuation dynamics of piezo transducers. Kelvin-Voigt viscoelastic model was introduced into the LISA formulation, which enables the modeling of wave attenuation in composites. In order to keep the model size manageable, non-reflective boundary techniques were encapsulated in LISA, which allows the simulation of wave propagation in an infinite domain using a finite size model. Furthermore, LISA's modeling capability was extended to include the nonlinear contact dynamics during wave interaction with fatigue cracks and delamination. The nonlinear guided wave techniques are promising candidates for SHM due to their distinctive nonlinear features and superb sensitivity to incipient damage. We also developed the strain sensing methodology using CLoVER transducer with analytical formulation and experimental study.

The GT-FSAT concept was developed as an effective active guided wave-based SHM system, and its design framework has been extended to composite structures. Moreover, conformability issues of the device have been tackled through the realization of a CLoVER/FSAT hybrid device. In addition, patterning of electrodes has been investigated for strain sensing applications through the Acoustic Wave Rosette concept. The FSAT has demonstrated its ability to locate damages on aluminum plates through pulse-echo operations. In addition, a new FSAT has been developed and successfully prototyped for operation on composites, where damage localization through pulse-echo operations produced results with similar accuracy to those gathered on aluminum. In addition, the *refined* hybrid CLoVER/FSAT, that addresses device conformability issues by adopting a flexible piezo-fiber active layer (prototyped during FY'14 by UM), has proved its capabilities in radiation mode. Another noteworthy development has been done towards the AWR prototyping and towards the study of a new device for the detection and localization of impacts in plate structures, which could find application for impact detection on fuselage and rotorblades.

Students supported under the project
1. Matteo Carrara – PhD awarded January 2016, currently Research Engineer, Apple Inc. Cupertino CA.
2. Dr. Yanfeng Shen– Postdoctoral Fellow, currently, Assistant Professor, Shanghai Jiao Tong University/U-M Joint Institute
3. Hui "Eric" Zhang– PhD Student
4. Kalyan Nadella – PhD awarded May 2014, postdoctoral fellow until Sept'14, currently at Ford Motor Co., MI

5. Matt Obenchain, Maj. USAF (US) – PhD awarded Aug 2014; currently Lead Systems Integration Engineer, KC-46 Program, Air Force Life Cycle Management Center, WPAFB, Ohio

Patents/Software Invention Disclosures
1. U.S. Patent No. 8,960,005. 24 Feb. 2015
2. FSAT Technology Licensed by GT to Aging Aircraft Consulting LLC

Publications

PhD Theses

1. Kalyan Nadella, "Numerical Simulation of Guided Waves in Thin Walled Composite Structures", *University of Michigan*, Ann Arbor, May 2014.
2. Matthew Bridger Obenchain, "Guided Wave Propagation and Damage Interaction in Isotropic and Composite Structures", *University of Michigan*, Ann Arbor, August 2014.
3. Matteo Carrara, "Fourier-based Design of Acoustic Transducers", *Georgia Institute of Technology*, Spring 2016. https://smartech.gatech.edu/handle/1853/448

Book Chapter

1. Shen, Y. and Cesnik, C.E.S., "Modeling Guided Wave Propagation in Composite Structures Using Local Interaction Simulation Approach," Chapter for Volume: Structural Health Monitoring for Advanced Composite Structures of Computational and Experimental Methods in Structures, edited by F. Aliabadi and Z. Khodaei, Published by World Scientific (under revision).

Journal Papers

1. E Baravelli, M Senesi, M Ruzzene, L De Marchi, "Fabrication and Characterization of a Wavenumber-Spiral Frequency-Steerable Acoustic Transducer for Source Localization in Plate Structures" IEEE Transactions on Instrumentation and Measurement, 2197 – 2204, 2013.
2. Nadella, K. and Cesnik, C.E.S., "Local Interaction Simulation Approach for Modeling Wave Propagation in Composite Structures," CEAS Aeronautical Journal, Vol. 4, No. 1, January 2013, pp. 35-48. doi: 10.1007/s13272-012-0061-9.
3. F Casadei, JJ Rimoli, M Ruzzene, "A geometric multiscale finite element method for the dynamic analysis of heterogeneous solids", Computer Methods in Applied Mechanics and Engineering, 2013.
4. Carrara, M., and Ruzzene, M., 2014, "Structural Health and Strain Monitoring Sensing Through Fourier-based Transducers", *Mechanics of Advanced Materials and Structures*, 22, 1-2 (pp 67-76), 2015.
5. Obenchain, M. B. and Cesnik, C. E. S., "Producing Accurate Wave Propagation Time Histories Using the Global Matrix Method," *Smart Materials and Structures*, Vol. 22, 125024 (11pp), Nov. 2013.
6. Obenchain, M. B. and Cesnik, C.E.S., "Guided Wave Interaction with Hole Damage Using the Local Interaction Simulation Approach," *Smart Materials and Structures*, Vol. 23, No. 12, 14pp, 2014.

7. Obenchain, M. B., Nadella, K. S., and Cesnik, C. E. S., "Hybrid Global Matrix/Local Interaction Simulation Approach for Wave Propagation Simulation in Composite Laminates," *AIAA Journal*, Vol. 53, No. 2, pp. 379-393, 2015.
8. Shen, Y. and Cesnik, C.E.S., "Hybrid Local FEM/Global LISA Modeling of Damped Guided Wave Propagation in Complex Composite Structures," *Smart Materials and Structures*, accepted July 2016.
9. Shen, Y. and Cesnik, C.E.S., "Modeling of Nonlinear Interactions between Guided Waves and Fatigue Cracks Using Local Interaction Simulation Approach," *Ultrasonics*, accepted September 2016.
10. Carrara, M. and Ruzzene M., "Damage Detection Capabilities of Spiral Frequency-steered Acoustic Transducers through Pulse-Echo Operations" (in preparation)

Conference Papers

1. Nadella, K.S. and Cesnik, C.E.S., "Numerical Simulation of Wave Propagation in Composite Plates," SPIE Smart Structures/NDE Joint Conference, San Diego, California, March 11-15, 2012.
2. Nadella, K.S. and Cesnik, C.E.S., "Simulation of Guided Wave Propagation in Isotropic and Composite Structures using LISA," 53rd *AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference*, Waikiki, Hawaii, April 23-26, 2012.
3. E. Baravelli, M. Senesi, D. Gottfried, L. De Marchi, M. Ruzzene, "Inkjet fabrication of spiral frequency-steerable acoustic transducers (FSATs)" SPIE Smart Structures/NDE Joint Conference, San Diego, California, March 11-15, 2012.
4. E. Baravelli, M. Senesi, D. Gottfried, L. De Marchi, M. Ruzzene, "Low power SHM via frequency-steerable acoustic transducers and compressive sensing", European Workshop on SHM – Dresden (Germany), July 2012.
5. F Casadei, J.J. Rimoli, M. Ruzzene "Multiscale analysis of wave-damage interaction in two and three dimensional isotropic plates" SPIE Smart Structures and Materials+ Nondestructive Evaluation Conference, March 2013.
6. Nadella, K.S. and Cesnik, C.E.S., "Piezoelectric Coupled LISA for Guided Wave Generation and Propagation," SPIE Smart Structures/NDE Joint Conference, San Diego, California, March 10-14, 2013. SPIE Paper No. 8695-63.
7. Obenchain, M.B, Nadella, K.S., and Cesnik, C.E.S., "Hybrid Global Matrix/Local Interaction Simulation Approach for Wave Propagation Simulation in Composite Laminates," 54th AIAA/ASME/ ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Boston, Massachusetts, April 08-11, 2013.
8. Nadella, K.S., Obenchain, M.B., and Cesnik, C.E.S., "LISA Modeling of CLoVER-generated Guided Waves and Their Interaction with Damage in Composite Structures," AHS 69th Annual Forum and Technology Display, Phoenix, Arizona, May 21-23, 2013.

9. M. Carrara, M. Ruzzene "Structural Health and Strain Monitoring Sensing Through Fourier-Based Transducers", Smart 2013 Conference, Turin Italy, June 2013.
10. Obenchain, M.B., Nadella, K.S., and Cesnik, C.E.S., "Hybrid Global Matrix/Local Interaction Simulation Approach for Damage Modeling in Composites," *Proc. 9th International Workshop on Structural Health Monitoring*, Palo Alto, California, September 2013.
11. Carrara, M., and Ruzzene, M., 2014, "Fourier-based Design of Acoustic Strain Rosettes", *Proceedings of the SPIE Smart Structures/NDE 2014*, San Diego, CA, 09-13 March 2014. SPIE Paper No. 9061-35.
12. Nadella, K.S. and Cesnik, C.E.S., "Effect of Piezoelectric Actuator Modeling for Wave Generation in LISA," SPIE Smart Structures/NDE Joint Conference, San Diego, California, March 9-13, 2014. SPIE Paper No. 9064-38.
13. Obenchain, M.B. and Cesnik, C.E.S., "Guided Wave Interaction with Defects in Isotropic and Composite Plates," SPIE Smart Structures/NDE Joint Conference, San Diego, California, March 9-13, 2014. SPIE Paper No. 9064-78.
14. Carrara, M., Nadella, K. S., Cesnik, C. E. S., and Ruzzene, M., "Development of a robust piezoelectric-fiber-based frequency steered acoustic transducer", *Proceedings of the 71st American Helicopter Society Annual Forum & Technology Display*, Virginia Beach, VA, on May 5-7, 2015.
15. Carrara, M., and Ruzzene, M., 2015, "New Trends In Multifunctional Sensors for Rotating Systems", *Proceedings of the AHS Technical Specialists' Meeting on Airworthiness, Condition Based Maintenance (CBM), and Health and Usage Monitoring (HUMS)*, Huntsville, AL, 09-11 February 2015.
16. Carrara, M., Ruzzene, M., 2015, "Frequency-Wavenumber Design of Spiral Micro Fiber Composite Directional Actuators", *Proceedings of the SPIE Smart Structures/NDE 2015*, San Diego, CA, 08-12 March 2015.
17. Shen, Y. and Cesnik, C.E.S., "Hybrid local FEM/global LISA modeling of guided wave propagation and interaction with damage in composite structures," *Proceedings of the SPIE Smart Structures/NDE 2015*, San Diego, CA, 08-12 March 2015.
18. Shen, Y., Zhang, H., Cesnik, C.E.S., "CLoVER Transducers for Static and Dynamics Strain Sensing," *Proc. 10th International Workshop on Structural Health Monitoring*, Palo Alto, California, September 2015.
19. Shen, Y. and Cesnik, C.E.S., "Modeling of Fatigue Crack Induced Nonlinear Ultrasonics Using a Highly Parallelized Explicit Local Interaction Simulation Approach," SPIE Smart Structures/NDE Joint Conference, Las Vegas, Nevada, 20-24 March, 2016. SPIE Paper No. 9805-23.
20. Zhang, H. and Cesnik, C.E.S., "A Hybrid Non-Reflective Boundary Technique for Efficient Simulation of Guided Waves using Local Interaction Simulation Approach," SPIE Smart Structures/NDE Joint Conference, Las Vegas, Nevada, 20-24 March, 2016. SPIE Paper No. 9805-30.
21. Shen, Y. and Cesnik, C.E.S., "In-situ Fatigue Damage Detection for Railway Structures Using Nonlinear Ultrasonic Guided Waves", 1st International

Workshop on Structural Health Monitoring for Railway System, Qingdao, China, 12-14 October, 2016.

22. Shen, Y. and Cesnik, C.E.S., "Efficient Modeling of Nonlinear Scattering of Ultrasonic Guided Waves From Fatigue Cracks Using Local Interaction Simulation Approach," Proceedings of the 2016 International Mechanical Engineering Congress & Exposition, IMECE2016, November 11-17, 2016, Phoenix, Arizona, IMECE2016-68197.

Awards

Project Technical Awards:

1. Best ASME/SPIE Student Paper Competition Carrara, M., Ruzzene, M., 2015, "Frequency-Wavenumber Design of Spiral Micro Fiber Composite Directional Actuators", *Proceedings of the SPIE Smart Structures/NDE 2015*

Faculty Technical Awards:

1. Massimo Ruzzene, Pratt & Whitney Professor of Aerospace Engineering, 2016
2. Carlos E. S. Cesnik, Fellow, RAeS, 2014
3. Carlos E. S. Cesnik, Fellow, AIAA, 2012
4. Carlos E. S. Cesnik,EMBRAER/Guido Pessotti Professor of Engineering, Instituto Tecnológico de Aeronáutica (ITA), Brazil, February 2015—February 2016
5. Carlos E. S. Cesnik, Benjamin Meaker Visiting Professor of Aerospace Engineering, University of Bristol, August—November 2014
6. Carlos E. S., Aerospace Engineering Department Award for Outstanding Accomplishment, 2013

Task 1.8 (GT-12): Reduced Order Linear Time Invariant Models and Algorithms for Integrated Flight/Rotor Control

PIs: J.V.R. Prasad (Georgia Tech), David A. Peters (Washington University), Peretz P. Friedmann (University of Michigan)

Background: Linear time periodic (LTP) models typical of rotorcraft problems are not suitable for control design since the majority of methods are based on linear models in time invariant (LTI) form. Also, handling qualities specifications are based on time invariant linear models and thus cannot be directly applied to the controller design using LTP models. Under a NASA NRA study at Georgia Tech, a computationally efficient scheme for extraction of LTI models in terms of body and harmonic rotor states from a nonlinear model was developed and validated in both time and frequency domain simulations.

The stability of LTI models with harmonic states converges to that of the periodic system when the number of harmonic states increases. However, the increase of harmonic states produces a high dimensional system. Therefore, the size of the LTI system has to be reduced. As a consequence of this reduction several issues arise: (a) sensitivity of model fidelity to the number of harmonic states employed, (b) effect of harmonic state feedback on stability margins and handling qualities.

Research Objectives: The overall goal of this task is the development of a LTI framework suitable for integrated flight and rotor On-Blade Control (OBC) design. The specific objectives are:
- Extract LTI models capable of capturing the effects of individual blade control (IBC) and OBC devices from a high fidelity nonlinear helicopter code.
- Develop a systematic and robust procedure for LTI model order reduction.
- Develop a robust methodology for assessing fidelity of reduced order LTI models.
- Develop a design framework that accounts for stability margins and handling qualities specifications in the presence of body and harmonic rotor state feedback for integrated flight and rotor control.
- Apply methods developed using integrated flight and rotor control examples.
- Explore opportunities for transition of the developed methodology and algorithms to industry and government labs.

Accomplishments: Two important questions that had to be addressed for fidelity assessment and LTI model order reduction were: (a) what are the most appropriate fidelity metrics?, and (b) how to determine the minimal order LTI model approximation of a periodic system? In order to answer these questions, a detailed understanding of stability properties of LTP and LTI models with harmonic states of rotor, body and inflow was developed. Numerical studies were carried out, after integrating the algorithms into FLIGHTLAB, to assess the effect of model order reduction with finite and selected harmonic states on model fidelity.

To establish a design framework capable of simultaneously accounting for stability margins and handling qualities in controller design, the CONDUIT tool was used and example evaluations were carried out. Towards this goal, new algorithms based on Fourier decomposition methods for estimation of harmonic rotor states from measurements that include rotor RPM variations were also developed. Extensive

batch and piloted simulation evaluations of the example controllers were carried out using the fixed-base rotary wing simulator at Georgia Tech.

The Fourier decomposition based method developed at Georgia Tech was used at University of Michigan to extract LTI models from a high fidelity nonlinear helicopter code like AVINOR. The nonlinear code accounts for IBC and OBC devices by incorporation of the HHC algorithm for vibration reduction, implemented by active flaps, combined with a CFD based reduced order aerodynamic model (ROM). The LTI models were verified against the nonlinear code at various flight conditions. Introducing aerodynamic states in the LTI models increases the size of the models. Therefore LTI model reduction methods have to be employed.

The potential for collaboration opportunities with government labs and industry for technology transitions were also explored.

The following is an list of accomplishments during each year of the project:

Year 1:
• Developed a methodology for assessing input-to-state fidelity of LTI model approximation of time periodic systems using modal participation factors.
• Established a procedure for LTI model order reduction using a newly developed fidelity metric based on modal participation factors.
• Evaluated the developed methodology for LTI model reduction for input-to-state fidelity using isolated rotor and full vehicle models from FLIGHTLAB.
• Implemented the Fourier decomposition based method into the AVINOR code in order to extract high fidelity LTI models capable of simulating IBC and OBC devices.

Year 2:
• Developed a method for calculating modal participation factors of a time periodic system directly from a full order LTI model. The developed procedure significantly reduces the computational effort involved in getting them from a time periodic model.
• Developed a methodology for assessing fidelity of input-to-output characteristics of LTI reductions from a full order model using error characterization as additive uncertainty in the frequency domain and as loss of stability margins using the gap metric analysis.
• Evaluated methodology using full vehicle models that include both rotor and inflow states from FLIGHTLAB.
• Extracted LTP/LTI models capable of capturing the effects of on-blade control devices from AVINOR, and determined the important role of augmented unsteady aerodynamic states.
• Input-to-output characteristics of the linearized models were verified for open-loop flap deflections at various flight conditions.

Year 3:
• Developed a LTI formulation for the time period model in first order form such as the case for body and inflow dynamics.
• Established that inflow harmonics to a greater extent and body harmonics to a lesser extent are important for achieving LTI model fidelity.
• Developed a model reduction approach using the balanced reduction which is based on Hankel singular values or state energy and evaluated the same using the UH 60E model in FlightLab.

- Assessed the design trade off needed for an existing harmonic estimator between performance and controller robustness as a precursor to exploring alternative harmonic estimators.
- Accuracy of the LTI models extracted from AVINOR was significantly enhanced by adding aerodynamic states in to the models.
- Closed-loop characteristics of the LTI models were verified for on-blade vibration control at various flight conditions.

Year 4:
- Computed modal participation showing body and inflow harmonic states have significant dynamics
- Collaborative work with AFDD on integrated flight/rotor control design using LTI models
- Developed a harmonic estimator using LTI models in a Linear Quadratic Estimator framework
- Order reduction performed on high fidelity linear models that can predict the effects of on-blade control on hub vibrations.
- The reduced-order models were verified for both open-loop and closed-loop vibration reduction at various flight conditions.

Year 5:
- Developed a standalone module to convert LTP to LTI with selectable order and balanced model order reduction for use in integrated flight/rotor control design. The module is being ported to FLIGHTLAB and RCAS.
- Carried out detailed off-design evaluations of integrated AFC/HHC controller in collaboration with AFDD.
- Completed time and frequency domain evaluations of LQE Harmonic Estimation. Conducted initial evaluation of effects of measurement noise on LQE performance.
- Incorporated a Doublet-Lattice (DL) based RFA unsteady aero model into RCAS. Developed model for MBB Bo-105 to allow comparison with results generated by AVINOR. This portion of the activity was extended, with additional funding, for a 10 month period beyond the end of the VLRCOE grant (January 2017).

Students and Researchers supported under the Project:

1. Dr. Mark Lopez, Ph.D., Georgia Tech, 2016. Currently with US AMRDEC AFDD at NASA Ames.
2. Chris Richardson, M.S., Georgia Tech, 2016. Currently with Aurora Flight Sciences.
3. Dr. Ashwani Padthe, Research Associate, University of Michigan.
4. Robert Walters, Ph.D. student, Georgia Tech, expected graduation: 2020.

Students worked on the project but not supported:

1. Nathan Morgan, M.S., Georgia Tech, 2015. With Boeing, Philadelphia.
2. Caitlin Berrigan, B.S., Georgia Tech, 2015, Currently with Textron Aviation.
3. Christopher Grusenmeyer, M.S., Georgia Tech, 2016. With Boeing Seattle.

Patents/Software/Invention Disclosures:

1. J.V.R. Prasad, Keeryun Kang, "Integrated Optimal Obstacle Avoidance (INTOPTOA) Algorithm for Autonomous UAV," GTRC ID 6018, Date: April 20, 2012.

List of publications:

Theses:

1. Lopez, Mark, "Linear Time Invariant Approximations of Linear Time Periodic Systems for Integrated Flight and Rotor Control," Ph.D. Thesis, Georgia Institute of Technology, 2016. https://smartech.gatech.edu/handle/1853/55599

Journals Papers:

1. Moon, Jongki and Prasad, J.V.R., "Minimum Time Approach to Obstacle Avoidance Constrained by Envelope Protection for Autonomous UAVs," IFAC Journal of Mechatronics, Vol. 21, No. 5, August 2011, pp. 861 – 875.
2. Yavrucuk, I. and Prasad, J.V.R., "Online Dynamic Trim and Control Limit Estimations using Adaptive Neural Networks Models," AIAA Journal of Guidance, Control and Dynamics, Vol. 35, No. 5, September – October, 2012, pp. 1647 – 1656.
3. Kang, K. and Prasad, J.V.R., "Development and Flight Test Evaluations of an Autonomous Obstacle Avoidance System for a Rotary-wing UAV," International Journal of Unmanned Systems, Vol. 1, No.1, July 2013, pp. 3-19.
4. Lopez, M. and Prasad, J.V.R., "Modal Participation of Linear Time Periodic Systems using Linear Time Invariant Approximations," Journal of the American Helicopter Society, Vol. 61, No. 4, October 2016.
5. Lopez, M. and Prasad, J.V.R., "Linear Time Invariant Approximations of Linear Time Periodic Systems," Journal of the American Helicopter Society, Volume 62, No. 1, January 2017.
6. Padthe, A., Friedmann, P. and Prasad, J.V.R., "High Fidelity Linear Time-Invariant Models for Closed-Loop Rotor and Flight Control Interaction Studies," Journal of the American Helicopter Society, Volume 62, No.1, January 2017.
7. Morgan, Nathan, Lopez, M., Caitlin, B. and Prasad, J.V.R., "Application of Linear Quadratic Estimation to Harmonic Analysis of Rotorcraft Vibration," Journal of Guidance, Control and Dynamics, Vol. 40, No. 9, September 2017.
8. Lopez, M., Tischler, M., Takahashi, M., Cheung, K. and Prasad, J.V.R., "Development and Evaluation of a Full Flight Envelope Integrated Flight and Vibration Controller," In review for publication in the Journal of the American Helicopter Society, June 2017.

Conference Papers:

1. Lopez, Mark and Prasad, J.V.R., "Linear Time Invariant Approximations of Time Periodic Systems," Proceedings of the 38th European Rotorcraft Forum, Amsterdam, Sept. 4-7, 2012.
2. Lopez, Mark and Prasad, J.V.R., "Fidelity of Reduced Order Time Invariant Linear (LTI) Models for Integrated Flight and Rotor Control Applications," Proceedings of the 69th Annual Forum of AHS International, Phoenix, Arizona, May 21-23, 2013.
3. Lopez, Mark and Prasad, J.V.R., "Periodic system Analysis Using a Linear Time Invariant Formulation," Proceedings of the 39th European Rotorcraft Forum, Moscow, Sept. 3-6, 2013.
4. Padthe, A., Friedmann, P. P., and Prasad, J. V. R., "High Fidelity Linear Time-Invariant Models for Rotor and Flight Control Interaction Studies", Proceedings of the Fifth Decennial AHS Aeromechanics Specialists' Conference, San Fransisco, CA, January 22-24, 2014.
5. Lopez, M., Mannivan, V., Prasad, JVR, Tischler, M.B., Takahashi, M.D. and Cheung, K. K., "HHC/AFCS Interaction and Performance using Piloted Simulation Evaluations," Proceedings of the AHS Rotorcraft Handling Qualities Specialists' Meeting, Huntsville, AL, February 19-20, 2014.
6. Padthe, A. and Friedmann, P.P., "Closed-Loop Fidelity Assessment of Linear Time-Invariant Helicopter Models for Rotor and Flight Control Interaction Studies," Proceedings of the 40th European Rotorcraft Forum, September 2 - 5, 2014, Southampton, UK.
7. Lopez, M., Prasad, J.V.R., Tischler, M. B., Takahashi, M. D., and Cheung, K. K., "Simulating HHC/AFCS Interaction and Optimized Controllers using Piloted Maneuvers," Proceedings of the 71st Annual Forum of AHS International, Virginia Beach, Virginia, May 5-7, 2015.
8. Lopez, M. and Prasad, J.V.R., "Linear Time Invariant Approximations of Time Periodic Systems," Proceedings of the 41st European Rotorcraft Forum, Munich, Germany, September 1-4, 2015.
9. Padthe, A. and Friedmann, P.P., Lopez, M., and Prasad, J. V. R., "Analysis of High-Fidelity Reduced-Order Linearized Time-Invariant Helicopter Models for Integrated Flight and On-Blade Control applications," Proceedings of the 41st European Rotorcraft Forum, Munich, Germany, September 1-4, 2015.
10. Lopez, M. and Prasad, J.V.R., "Linear Time Invariant Approximations of Time Periodic Systems," Proceedings of the 41st European Rotorcraft Forum, Munich, Germany, September 1-4, 2015.
11. Morgan, N., Lopez, M., Caitlin, B. and Prasad, J.V.R., "Application of Linear Quadratic Estimation (LQE) to Harmonic Analysis of Rotorcraft Vibration," Proceedings of the 72nd Annual Forum of AHS International, May 17-19, West Palm Beach, Florida, May 17-19, 2016.
12. Grusenmeyer, C. and Prasad, J.V.R., "A LTI/LQE Scheme for Estimation of Harmonic Components of Rotorcraft Hub Loads," Proceedings of the 5th Asia - Australia Rotorcraft Forum, Singapore, November 17 – 18, 2016.

Awards:

Team Technical Awards:

1. Journal best paper award from the *Journal of Unmanned Systems*, 2015: Paper authors and title: Kang, K. and Prasad, J.V.R., "Development and Flight Test Evaluations of an Autonomous Obstacle Avoidance System for a Rotary-wing UAV," International Journal of Unmanned Systems, Vol. 1, No.1, July 2013, pp. 3-19.

Faculty Technical Awards:

1. Dr. David A. Peters, American Institute of Aeronautics and Astronautics Reed Aeronautics Award, 2011.
2. Dr. J.V.R. Prasad, AIAA Fellow, 2012
3. Dr. David A. Peters, American Society of Mechanical Engineers Spirit of St. Louis Medal, 2013.
4. Dr. Peretz Friedman, AHS Alexander A. Nikolsky Honorary Lectureship, 2013.
5. Dr. J.V.R. Prasad, AHS Technical Fellow, 2014.
6. Dr. David A. Peters, Inaugural Distinguished Lecturer, Union University, Jackson, TN, 2015.
7. Dr. J.V.R. Prasad, The AeroLion Technologies Outstanding Journal Paper Award, International Journal of Unmanned Systems, December 2015.
8. Dr. Peretz Friedmann, Meir Hanin International Aerospace Prize awarded by The Technion, Israel Institute of Technology, 2016.

Student Technical Awards:

None to Report

Technology Transfer:

- Developed a standalone module to convert LTP to LTI with selectable order and balanced model order reduction for use in integrated flight/rotor control design. The software is used in the current VLRCOE project by prof. Joseph Horn at Penn State.
- Collaborated with Drs. Mark Tischler and Mark Takahashi on "Design of Integrated AFCS and HHC Logic for Rotorcraft," (2013 –'16).

Task 1.9 (GT-15): Affordable Material Qualification for Composite Rotorcraft Structures

PIs: Andrew Makeev (Univ of Texas-Arlington), Daniel Schrage (Georgia Tech)

Research Objectives: The objective of this Task is to advance our ability to predict material behavior in order to enable more affordable/effective qualification of composite materials for rotorcraft structures: In particular, improve our understanding of complex deformation and failure mechanisms in composites and accordingly more heavily rely on analysis to capture multidirectional laminate strength and fatigue behavior. More specifically, develop methodology measuring the key lamina properties with the minimum number of test methods and replacing laminate coupon-level tests currently used in the material qualification with verified computational models (virtual tests) thus increasing efficiency of qualification (time is money) and expanding material design space.

Background and Accomplishments: Historically, analysis has not been considered adequate for predicting the key laminate-level properties from the lamina-level basic material characteristics. Among the challenges to the development of the adequate common analysis methods are sensitivity of composites to out-of-plane stresses; inaccurate out-of-plane failure prediction using tools available to structural engineers; the lack of accurate out-of-plane material characteristics; and the multiplicity of composite failure modes. Despite great multiplicity of standard lamina test methods, such methods do not seem to capture all material properties which might be key to analysis able to predict laminate strength and fatigue behavior.

If the qualification of composite materials for future vertical lift structural designs can more heavily rely on analysis so the amount of the required testing can be reduced, the qualification will be more affordable. Our plan has been to: (A) start at the base of the building block approach and minimize the amount of the lamina-level testing accurately measuring all key basic material properties; (B) rely on analysis for predicting laminate/element strength and fatigue characteristics and reduce the testing requirements to analysis verification testing; and (C) determine a path forward to enabling accurate structural strength and fatigue predictions for larger and more complex structures.

(A) We have been successfully executing this plan and have developed methodologies based on greatly reduced lamina testing accurately measuring the basic material properties. Among significant contributions started has been successful development and verification of the fundamental methods driven by Digital Image Correlation (DIC) and Computed Tomography (CT) data to capture physics of the investigated phenomena including stress-strain response, strength/fatigue and toughness material characteristics. Over the last five years we have been developing the DIC-based and CT-based advanced measurement techniques for material characterization as well as effective analysis methods to verify simplifying assumptions and increase our confidence in material allowables for laminated composite systems. The DIC-based methods developed at the University of Texas Arlington (UTA) Advanced Materials and Structures Lab (AMSL- http://www.uta.edu/mae/AMSL) to determine lamina stress-strain

curves in three dimensions and mode strength/fatigue characteristics include (1) Short-Beam Shear (SBS) Method, and (2) Small-Plate Twist (SPT) Method – simultaneously measuring nonlinear three-dimensional material properties. Our methods have been verified for legacy and advanced polymeric composite material systems. Our DIC data-driven methods are being successfully transitioned to Rotorcraft Industry under NRTC/VLC Project, Common Material Qualification for Laminated Composites Improving Confidence in Material Allowables, which is a team effort with Sikorsky Aircraft – Lockheed Martin Company; and the methodology has been recently verified by Boeing. The Air Force Research Lab (AFRL) Composite Airframe Life Extension (CALE) has been among many programs which successfully used our unique methods for composite material characterization to meet the input data requirements for progressive damage analysis of multi-directional laminated composite structures. Dr. Steven Clay is CALE program manager.

(B) We demonstrated that these basic material properties can be successfully used in FE-based structural analysis for strength and fatigue predictions in laminated coupons and elements: ASTM D5766 OHT; ASTM D6484 OHC; OH fatigue; lug bearing; notched bending/shear flapping element strength and fatigue; stringer element; including the effects of defects, etc.. Our original methods for accurate laminate analysis, including strength and fatigue progressive failure prediction to detectable damage sizes, have been successfully demonstrated up to structural elements. To meet the requirement of predicting structural damage progression to ultimate strength and fatigue of composite structures, we were able to eliminate convergence issues associated with large cracks and delaminations near ultimate strength by shifting from Implicit to Explicit FEM formulation.

(C) To enable accurate structural strength and fatigue predictions for larger and more complex composite aircraft structures up to components we must capture their manufacturing complexity and variability. A path forward includes developing integrated NDI, structural diagnostics, and structural strength/fatigue prognosis capturing multiple damage modes and their interaction and supported by structural validation testing. Increased manufacturing complexity can be transferred to progressive damage analysis through high-fidelity NDI and automated transition of defect information to structural models. Our original methodology integrates nondestructive structural diagnostics capturing the critical defects with automated transition to structural FEM; accurate material characterization methods capturing 3D mechanical properties including nonlinear behavior; and comprehensive structural strength/fatigue prognosis methods able to capture multiple damage modes and their interaction. We have been increasing complexity and size of structural verification articles, the most recent published examples included 2 foot long and 0.5 in. thick IM7/8552 carbon/epoxy flapping elements with a lay-up representative of a yoke structure; and 2.5 foot long IM7/8552 skin and hat-section stiffener elements – all articles built by Bell Helicopter Textron. We demonstrated remarkable 95% accurate strength and 80% accurate fatigue life predictions for the elements with manufacturing defects including wrinkles and voids.

Again, to enable accurate structural strength and fatigue predictions for larger and more complex composite structures up to components we must capture their manufacturing complexity and variability. We believe that a successful path forward will be expanding our integrated state-of-the-art material characterization methods and prognostics capabilities enabling: (1) Accurate nondestructive three-dimensional measurement of manufacturing irregularities and structural damage including the defect location and size with automated transition to structured finite element models; (2) Accurate and cost-effective material characterization to capture 3D material properties using the minimum number of experiments; and (3) Comprehensive strength and fatigue prognosis methods capturing multiple damage modes and their interaction in composites. Furthermore, we must move forward developing the composite process simulation tools able to predict the critical defects including voids and fiber-waviness; and integrating them with our tools for structural diagnostics and performance prediction will be essential for closing the loop on effective control of manufacturing processes to minimize formation of the critical defects.

Students supported under the project:
1. Guillaume Seon, Ph.D. graduated spring 2014, now engineering research scientist at UTA
2. Michael Tadros, Ph.D. graduated spring 2015
3. Julia Cline, Ph.D. graduated summer 2015, now at ARL.
4. Ekaterina Bostaph, Ph.D. graduated summer 2017, now at SpaceX

Patents/Software Invention Disclosures:

None

Publications:

Theses

1. Guillaume Seon, "Finite Element based Methodology for Prediction of Matrix-Dominated Failure in Composites"
2. Michael Tadros "Novel Device and Methods for Composite Material Characterization"
3. Julia Cline, "Accurate Three-Dimensional Characterization of the Nonlinear Constitutive Properties of Laminated Composite Materials"
4. Ekaterina Bostaph, "Advanced Methods of Nondestructive Inspection of Composite Structures Based on Limited Angle X-Ray Computed Tomography"

Journal Papers

Our recent research accomplishments are documented in more than 20 articles in the top refereed journals in the field.

Conference Papers

No details provided

Awards:

Team Technical Awards

Recognized by five "best paper" awards at national and international conferences including the Cheeseman Award at the 36th European Rotorcraft Forum (the first and only time awarded to authors based in the United States); 2013, 2014, and 2016 American Helicopter Society Forum best papers in structures and materials; and the American Society for Composites best paper award in 2013.

Faculty Technical Awards

No details provided

Student Technical Awards

No details provided

Technology Transfer:

No details provided

Task 1.10 (GT-16): Diagnostics For Transient Multidimensional Rotorcraft Flows

PIs: N.M. Komerath (GIT) and James Gregory (The OSU)

Background: The grand challenge of this task was to advance diagnostic techniques needed to capture the pressure and velocity fields seen on a rotor blade in forward flight, in a wind tunnel. Work at OSU was focused on developing the diagnostics science of pressure-sensitive paint, under highly accelerated conditions. Rotation and flapping blade motion posed strong challenges in image correction for both PSP and PIV. Blurring of the blade edges within the finite gate time of the image, and cycle-to-cycle variations in blade position defeat cycle averaging. The longer lifetimes of high-sensitivity PSPs aggravate the blade blurring problem. The dynamic response challenges of PSP were also overcome, leading to >7-kHz bandwidth. Work at GIT advanced particle image velocimetry and the off-surface flowfield around the retreating blade and analogous problems.

Research Objectives: Advance the capability to capture fundamental, 4-dimensional properties towards controlling transient flow problems.

Summary of Accomplishments: Development of PSP at Ohio State involved tailoring the paint chemistry; benchtop evaluation of the paint dynamic response characteristics; development of data processing techniques such as POD, DMD, and image deblurring; and small-scale wind tunnel demonstration of PSP capabilities. The development strategy involved assessment of various luminescent molecules in the paint formulation, and the energy transfer and interactions between multiple luminophore components. Benchtop evaluation of paint response involved static calibration in a pressure- and temperature-controlled chamber, while dynamic response characterization was performed in a one-dimensional standing-wave tube. Wind tunnel assessment of data acquisition methods was performed on a small-scale rotor in a 3'x5' open return wind tunnel. PSP formulations and data acquisition techniques were then applied in conjunction with PIV in the GIT 7'x9' wind tunnel for study of dynamic stall on a rotor in forward flight.

GIT experiments using PIV and Particle Tracing Velocimetry derived acceleration in a standing acoustic wave, as well as of larger particles in an acoustic field, as validated using COMSOL finite element CFD up to 800Hz. Acceleration capture from high-frequency velocity data despite experimental errors lent confidence. A rotating disk was used to capture a thin boundary layer under radial stress using micro PIV.

A first attempt was made in 2014 with PIV and PSP with the same laser under a rotating blade in reverse flow in the GT 7' x 9' tunnel (7-foot rotor, 200 RPM, advance ratio up to 1.) Several issues prevented extraction of a clear pressure distribution in this low-dynamic-pressure case at such large distances. We changed direction under guidance from the Review Panel.

PSP frequency response was verified via dynamic calibrations, with a flat response out to at least 7 kHz. Step response calibrations of PSP showed the effect of surface roughness, luminophore and the final pressure. Due to non-

linearity, the pressure jump magnitude and direction are important for comparison of response times of different PSP compositions. Response times have been obtained for step decrease in pressure (which is difficult to capture in experiments). Image Derotation of PSP has been pursued, based on image deconvolution methods, and physical rotation of a mirror, with both techniques being feasible for effective derotation. Error propagation due to a misaligned mirror remains to be analyzed.

At GIT, we focused on extracting static pressure fields from measured velocity data in incompressible flows. Stereo PIV with closely-spaced planes was used in 2015 on the reverse flow rotor and the Aspect Ratio 1 cylinder in yaw. Mass conservation was used to align and reduce error in 3-D velocity fields. Interpolated on to a computational grid, this provided the known velocity along with a first-guess static pressure field as input to a Navier-Stokes solver, which then iterated to the correct pressure field including effects of work and shear losses. A Lagrangian streamline computation used Couette Flow showed that errors due to viscous effects were small.

The pressure extraction technique has broken through in 2016. The obstacle had been in separated flow zones where there was no good initial guess for static pressure. This was obtained from the streamline curvature of the flow at the edge of the separated zone, following the Polhamus suction analogy. A numerical test case was developed. The velocity field computed around a 2-d cylinder at Reynolds number of 40 (attached steady Foeppl Vortex regime) was used, along with guess of static pressure based on streamline curvature. The excellent agreement with the actual computed static pressure field lent confidence. The same method was used with the SPIV data obtained on the side of the yawed AR1 cylinder from Task 10A. The pressure matched the actual static pressure measured on the side of the cylinder using pressure sensors, and give much better signal-to-noise ratio than the pressure sensors can deliver. Comparison with PSP results from OSU were satisfactory, to the extent permitted by the preliminary PSP results that could be obtained. These have been reported in an ASME paper to be presented in November 2017. Analysis of the velocity and pressure fields in the rotor case in the reversed-blade condition at high advance ratio, is being completed with Nandeesh Hiremath's PhD thesis. For low-speed flows, this velocity-based pressure extraction offers a superior alternative to other techniques including direct single-point sensors.

OSU conducted PSP on the small-aspect ratio cylinder in a quasi-steady yaw condition. These face leading edge problems in PSP development. To capture the instantaneous pressure on a moving body we compared two methods for acquiring the pressure data. The first method is to use the self-referencing single-shot technique with a PIV laser. The laser enabled acquisition of non-sequential, instantaneous PSP images. The second method used a high-speed camera system, with bright LED excitation for acquiring data even under low dynamic pressure conditions.

With the above, we submit that the original problem that of being able to capture the static pressure field around a rotor in reversed flow with sufficient

resolution to obtain the pitching moment, has been solved at least in demonstrating capability.

Progress towards obtaining the actual pitching moment was made using a final lset of experiments in Winter 2017, using our new high-speed SPIV system and the new pressure extraction technique. The pressure extraction technique validated above using the yawed-cylinder case has been used with the reversed-blade rotor data, and shows success in capturing the vortex-induced flowfield, including the separated flow regions. Thus the basic capability to extract the pressure field, and hence the pitching moment, has been demonstrated under this diagnostics-development project. It does require intensive 3-component, high-speed stereo PIV measurements, which are beyond the scope of where we could reach in this project.

Students supported under the project:

1. Vrishank Raghav, (MSAE, GIT; PhDAE, GIT, 2015. AE Faculty, Auburn U.)
2. Di Peng, (PhDAE, The OSU, 2014. Faculty, P.R.China)
3. Nandeesh Hiremath, (MSAE, GIT; PhD program, GITAE)
4. Dhwanil Shukla, (MSAE, GIT; PhD program, GIT)
5. Anshuman Pandey (PhD AE, The OSU 2016)
6. Michael Mayo (MSAE, 2014; GTRI)
7. Natasha Barbely (MSAE, 2014; PhD program, GITAE; NASA Ames)
8. Nicklaus Thorell (MSAE, 2015; Sandia National Labs, CA)
9. Sorin Pirau (MSAE 2014; Pratt & Whitney)
10. Nicholas Motahari (MSAE 2016; Pratt & Whitney),
11. Jackson Merckl (BSAE 2017)
12. Brandon Liberi (BSAE 2015, Raytheon Co.)
13. Vaibhav Kumar (BSAE 2017; MSAE program GITAE)
14. Joseph Robinson (BSAE 2017; MSAE program GITAE)
15. Zujia Huang (BSAE 2017; MSAE program GITAE),
16. Current GIT BSAE students: Bryan Libermann, Emily Hale, Zach Palmer, Ryan McMullen, David Huynh,
17. OSU BSAE student: Kevin Williams

Patents/Software Invention Disclosures:
None

Technical Awards
Team Technical Award

1. J. Gregory, Alfred Gessow Best Paper Award (2012),

Faculty Technical Awards

1. N. Komerath, AIAA(2016) and ASEE(2015) John Leland Atwood Education Award

2. J. Gregory, US Fulbright Scholar Award (2014)
3. J. Gregory, AIAA Associate Fellow (2016),
4. J. Gregory, NASA Group Achievement Award (2013),
5. J. Gregory, Alfred Gessow Best Paper Award (2012),
6. J. Gregory, SAE Ralph Teetor Award (2012)

Student Technical Awards
1. Vrishank Raghav (2015) Georgia Tech Sigma Xi Outstanding PhD Thesis Award.
2. Sorin Pirau (2014) Vertical Flight Foundation Scholarship
3. Brandon Liberi (2014) Vertical Flight Foundation Scholarship
4. Brandon Liberi, 2014: Outstanding Undergraduate Researcher, COE, Georgia Tech
5. Jackson Merkl (2015) PURA
6. Jackson Merkl, Vertical Flight Foundation Fellowship
7. Dhwanil Shukla (2015) Vertical Flight Foundation Scholarship
8. Vaibhav Kumar (2015) Vertical Flight Foundation Scholarship
9. Nandeesh Hiremath (2017) Vertical Flight Foundation Scholarship
10. Kevin Williams (2016) Vertical Flight Foundation Scholarship

Publications
Journals:

1. Raghav, V., Komerath, N., Instability of the radial flow over a rotating disk in a separated edgewise stream. Physics of Fluids, 25.11 (2013): 111701.
2. Raghav, V., Komerath, N., Velocity measurements on a retreating blade in dynamic stall. Experiments in Fluids, 55.2 (2014): 1-10.
3. Mayo, M., Raghav, V.S., Komerath, N.M., Vortex Flow Hypothesis For a Yawed Rotor Blade in Reverse Flow. Proc IMechE Part G:J Aerospace Engineering, Sage Publishing Co., UK 2014.
4. Disotell, KJ* and Gregory, JW, 2011, "Unsteady Surface Signature of a Pulsed Vortex Generator Jet," *Journal of Visualization*, v. 14, n. 2, pp. 121-127, doi: 10.1007/s12650-011-0080-3. IF: 0.575
5. Juliano, TJ*, Kumar, P*, Peng, D*, Gregory, JW, Crafton, J, and Fonov, S, 2011, "Single-shot, lifetime-based pressure-sensitive paint for rotating blades," *Measurement Science & Technology*, v. 22, no. 8, pp. 085403, doi: 10.1088/0957-0233/22/8/085403. IF: 1.433
6. Disotell, KJ* and Gregory, JW, 2011, "Measurement of Transient Acoustic Fields Using a Single-Shot Pressure-Sensitive Paint System," *Review of Scientific Instruments*, v. 82, no. 7, pp. 075112-1-8, doi: 10.1063/1.3609866. IF: 1.614
7. Fang, S*, Long, S*, Disotell, KJ*, Gregory, JW, Semmelmayer, FC, and Guyton, RW, 2012, "Comparison of Unsteady Pressure-Sensitive Paint Measurement Techniques," *AIAA Journal*, v. 50, n. 1, pp. 109-122, doi: 10.2514/1.J051167. IF: 1.207

8. Juliano, TJ*, Disotell, KJ*, Gregory, JW, Crafton, J, & Fonov, S, 2012, "Motion-Deblurred, Fast-Response Pressure-Sensitive Paint on a Rotor in Forward Flight," *Measurement Science & Technology*, v. 23, n. 4, 045303, doi: [10.1088/0957-0233/23/4/045303](10.1088/0957-0233/23/4/045303). IF: 1.433

9. Peng, D*, Jensen, CD*, Juliano, TJ*, Gregory, JW, Crafton, J, Palluconi, S, and Liu, T, 2013, "Temperature-Compensated Fast Pressure-Sensitive Paint," *AIAA Journal*, vol. 51, no. 10, pp. 2420-2431, doi: [10.2514/1.J052318](10.2514/1.J052318). IF: 1.207

10. Gregory, JW, Sakaue, H, Liu, T, and Sullivan, JP, 2014, "Fast Pressure-Sensitive Paints for Flow and Acoustic Diagnostics," *Annual Review of Fluid Mechanics*, vol. 46, pp. 303-330, doi: 10.1146/annurev-fluid-010313-141304. IF: 11.163

11. Disotell, KJ*, Peng, D*, Juliano, TJ*, Gregory, JW, Crafton, J, and Komerath, NM, 2014, "Single-Shot Temperature- and Pressure-Sensitive Paint Measurements on an Unsteady Helicopter Blade," *Experiments in Fluids*, vol. 55, 1671, doi: [10.1007/s00348-014-1671-2](10.1007/s00348-014-1671-2). IF: 1.670

12. Gregory, JW, Disotell, KJ*, Peng, D*, Juliano TJ*, Crafton, J, and Komerath, NM, 2014, "Inverse Methods for Deblurring PSP Images of Rotating Surfaces," *AIAA Journal*, vol. 52, no. 9, pp. 2045-2061, doi: [10.2514/1.J052793](10.2514/1.J052793). IF: 1.207

13. Peng, D* and Gregory, JW, 2015, "Vortex dynamics during blade-vortex interactions," *Physics of Fluids*, v. 27, no. 053104, doi: [10.1063/1.4921449](10.1063/1.4921449). IF: 2.031

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15. Pandey, A* and Gregory, JW, 2016, "Frequency Response Characteristics of Polymer/Ceramic Pressure-Sensitive Paint," *AIAA Journal*, v. 54, no. 1, pp. 174-185, doi: [10.2514/1.J054166](10.2514/1.J054166). IF: 1.207

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Conference Papers:

1. Barbely, N., Pirau, S., Komerath, N.M., Measurements Of Wall Formation Forces In An Acoustic Resonator. Peer Reviewed Paper ASME IMECE2013-63307, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* San Diego, USA, November 15-21, 2013,

2. Raghav, V., Komerath, N.M., Boundary Layer Measurements on a Rotating Disk. Peer Reviewed Paper ASME IMECE2013-63556, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* November 15-21, 2013, San Diego, USA

3. Mayo, M.G, Motahari, N., Raghav, V.S, Komerath, N.M., Vortex Flow Hypothesis for Rotor Blades in Reverse Flow. Peer Reviewed Paper ASME IMECE2013-63957, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* November 2013, San Diego, USA

4. Shukla, D., Hiremath, N., Raghav, V., Komerath, N., Dynamic Effects in the Reverse Flow Velocity Field. Peer Reviewed Paper, *Proceedings of the KSME/JSMEASME Joint Fluids Engineering Conference*, Seoul, July 2015.

5. Merkl, J., Hiremath, N., Raghav, V., Komerath, N., Gregory, J., Extracting Static Pressure from Velocimetry in Vortical Flows. Peer Reviewed Paper, *Proceedings of the KSME/JSMEASME Joint Fluids Engineering Conference*, Seoul, July 2015.

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8. Shukla, D., Hiremath, N., Komerath, N., Vortical Features of a Rotor Blade in Reversed Flow. Peer Reviewed Paper ASME IMECE2015-52518, *Proceedings of the ASME International Mechanical Engineering Conference and Exposition,* Houston, November 2015.

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10. Kumar, V., Thorell, N., Komerath, N., Dielectric Barrier Discharge Actuators to Control Goertler Vortices on a Swept Wing. Peer Reviewed Paper ASME FEDSM2016-7688, *Proceedings of the ASME Fluids Engineering Conference,* Washington DC July 2016.

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12. Hiremath, N., Shukla, D., Huang, Z., Komerath, N., Pressure Fields Around a Rotor Blade in Reverse Flow. Peer Reviewed Paper ASME FEDSM2016-7685, *Proceedings of the ASME Fluids Engineering Conference*, Washington July 2016.

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14. Thorell, N., Kumar, V., Shukla, D., Komerath, N., Yaw Effects on the Narrowband Spectra Above a Delta Wing in Turbulent Flow. Peer Reviewed Paper, *Proceedings of the SAE Aerospace Systems Conference*., Hartford, Sep. 2016.

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25. Peng, D* and Gregory, JW, 2014, "Experimental Study of Vortex Dynamics during Blade-Vortex Interactions," *Proceedings of the 52nd AIAA Aerospace Sciences Meeting* (AIAA 2014-1284), National Harbor, MD, January 13-17, 2014.† doi: 10.2514/6.2014-1284

26. Pandey, A* and Gregory, JW, 2015, "Dynamic Response Characteristics of Polymer/Ceramic Pressure-Sensitive Paint," *Proceedings of the 53rd AIAA Aerospace Sciences Meeting* (AIAA 2015-0021), Kissimmee, FL, January 5-9, 2015.†# doi: 10.2514/6.2015-0021

27. Disotell, KJ*, Nikoueeyan, P, Naughton, J, and Gregory, JW, 2015, "Single-Shot Pressure-Sensitive Paint Measurements of Static and Dynamic Stall on a Wind Turbine Airfoil," Paper No. 38, *Proceedings of the American Helicopter Society 71st Annual Forum*, Virginia Beach, VA, May 5-7, 2015.†#

28. Pandey, A* and Gregory, JW, 2015, "Step Response of Polymer/Ceramic Pressure Sensitive Paint", *Proceedings of the 10th Pacific Symposium on Flow Visualization and Image Processing* (PSFVIP 10-49), Naples, Italy, June 15-18, 2015.†#

29. Pandey, A*, Gregory, JW, Stanfield, S, and Crafton, J, 2016, "Comparison of Blur Elimination Techniques for PSP Images of Rotating Surfaces," *Proceedings of the 54th AIAA Aerospace Sciences Meeting* (AIAA 2016-2019), San Diego, CA, January 4-8, 2016.† doi: 10.2514/6.2016-2019

Technical Transfer

Deblurring codes based on image deconvolution. Contact: Dr. A. Neal Watkins (NASA Langley); Dr. Oliver Wong (Army)

Task 1.11 (GT-18): High Performance External Cargo Operations

Principal Investigator
Eric Johnson (eric.johnson@ae.gatech.edu)

Background
The logistics of supplying materials where needed is a major effort in all military theaters of operation, as well as in disaster response as seen in recent events in Japan. It represents a major driver in cost, risk to personnel, and overall effectiveness of military elements at any level. For some time there has been the capability for manned helicopters to transport sling loads and perform pickup/drop-off at desired specific geographic locations. The sling-load system is not always stable and pilots have been forced to limit top speed and even jettison unstable cargo in flight. The ability to safely and precisely place the load is a major limitation for ship resupply via this method (particularly at night or in sea state). This is seen as an important mission of, for example, proposed variants of the Northrop Grumman RQ-8A Fire Scout UAS. These operations are an impressive reproduction of what manned helicopters can already do. The proposed challenge is to take these ideas to the next logical step, to enable operations that are not practical with current aircraft systems. Specifically, we have developed systems whereby a helicopter can automatically rapidly deliver cargo with precision onto and off-of a moving platform (such as a ship). This implies higher speeds, higher accelerations/jerk, and greater precision. This required fundamental research in methods for guidance (account for motion of sling load), measurement/estimation of load state (for use in integrated flight control), measurement/estimation of target state (for use in integrated guidance and flight control while precisely placing load), and integrated flight control (sling load pendulum modes will couple strongly with aircraft motion states).

Research Objectives:
- Determine and quantify the limiting factors on sling load maximum speed, acceleration/jerk, and load placement precision. This will heavily leverage past work in this area and our external collaborators. This will include knowledge of pendulum mode state, knowledge of target state, load design parameters (line placements, line length).
- Develop pendulum mode and target state estimation methods suitable for high performance sling load delivery, including potential measurement strategies such as an instrumented load/target and vision-based methods.
- Develop integrated guidance and flight control methods that enable agile load motion, operating at design points where significant load/helicopter coupling is taking place (short line lengths) and operating near the limits of possible velocity, acceleration, and jerk.
- Develop integrated guidance and flight control methods that enable precise load placement, where the control objective relates to an end-game of minimizing load/target position error at time of contact.

- Collaborate with companion task on bluff body aerodynamic modeling to enhance simulation tools for helicopter sling loads.
- Carry out simulation evaluations of the methods developed.
- Perform flight test validation of the simulation results.
- Achieve technology transition of these ideas to currently under development unmanned systems as well as future highly-augmented and/or optionally manned helicopters.

Accomplishments: The team validated potential to improve sling load operations by interviews with military pilots and review of several documents related to sling load operations. In particular, the speed and availability can potentially be improved by the methods we have developed in this effort.

The team improved its real-time pendulum state estimation system to the point that it is suitable for all anticipated testing under the effort. This was done based on recorded images from flights over particularly difficult terrain. The methods developed have the potential to result in minimal instrumentation for use of automation in sling load operations. We have added the ability for the sling to be automatically released under fault/emergency scenarios as well as to allow automated release of the sling load at a precise location. This system was successfully test flown in several flight test series under the effort. An automatic load release system was developed and utilized to support planned flight validation activities.

The core of the effort and contribution has been the exploration of several methods for doing real-time path planning accounting for sling dynamics. This has included theory, simulation, and in flight testing of the most promising methods. This has included non-linear trajectory generation (NTG), Differential Dynamic Programming (DDP), and Rapidly exploring Random Tree (RRT) methods. The team found that each has a potential for producing fast/robust solutions – even in the presence of model error and disturbances. They do have advantages and disadvantages, which have been documented. Along the way, the team also expanded on the use of Variational Integrators (VI), which can be utilized to improve all of these methods for systems. VIs have been found to dramatically improve the amount of processing required to compute optimal solutions for the trajectory of the aircraft when the system is approximately energy conserving (a property of a swinging load). The effort included what was perhaps the first ever flight testing of a VI-enabled planning method.

We have prepared for a series of final flight testing activities which have been delayed. They are now scheduled for May 2017.

Students supported under the project
1. Gerardo De La Torre (USA): supported 50% time, 2013-2015, PhD awarded August 2015, post-doctoral researcher at Northwestern University.
2. John Mooney (USA): supported 50% time 2012-2015, current PhD student and Guidance and Control Engineer with Google Project Wing.
3. Takuma Nakamura (Japan): supported 50% time briefly in 2015, current PhD student.
4. Stephen Haviland (USA): supported 50% time, 2015, current PhD student

5. Dmitry Bershadsky (USA): supported 50% time, 2015, current PhD student

Patents/Software Invention Disclosures
None to report

Publications

Journal papers:

1. De La Torre, G., Theodorou, E., and Johnson, E.N., "Autonomous Suspended Load Operations via Trajectory Optimization and Variational Integrators," *AIAA Journal of Guidance, Control, and Dynamics*, November 2016.

Conference Papers:

1. De La Torre, G., Johnson, E.N., and Theodorou, E., "Guidance for Slung Load Operations through Differential Dynamic Programming," *AHS Forum*, May 2014.
2. Johnson, E.N. and Mooney, J.G., "Longitudinal Motion Planning for Slung-Loads Using Simplified Models and Rapidly-Exploring Random Trees," *AHS International Specialists Meeting on Unmanned Rotorcraft and Network Centric Operations*, January 2015.
3. Nous, C., De La Torre, G., and Johnson, E.N., "Trajectory Generation for Slung Load Operations via DDP with State and Input Constraints," *41st European Rotorcraft Forum*, September 2015.
4. Johnson, E.N. and Mooney, J.G., "Steer Function for Pop-Limited Two-Dimensional Double Integrator," *AIAA Guidance, Navigation, and Control Conference*, January 2016.

Awards
Student Technical Awards

1. Gerardo De La Torre: Goizueta Foundation Fellowship, 2012-2015
2. First place AHS Autonomous Micro Air Vehicle Competition, 2015

Technical Transfer
None to report

Task 1.12 (GT-20): Conceptual Modeling of Electric and Hybrid-Electric Propulsion for UAS Applications

PIs: Dimitri Mavris (Georgia Tech) and Kyle Collins (Georgia Tech)

Background: In recent years, there has been a push towards greater use of renewable energy sources to meet environmental challenges by lowering overall carbon emissions. To that effect, EVs and HEVs have been developed in mass, and their performance is improving significantly as electric technology develops. Being less dependent on fuel, EVs and HEVs produce fewer overall emissions when compared to their gas-powered counterpart, and their cost of operation is also generally lower and less volatile, though they tend to be more expensive and suffer from reduced range. The Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology has developed models of components used in hybrid-electric propulsion systems and other algorithms to allow the conceptual sizing and performance analysis when applied to rotary wing air vehicles up to 1,300 pounds. The overall project contains three tasks. Task 1 develops component models that can be used to size and model hybrid-electric propulsion systems for rotary wing vehicles in the size range specified. Task 2 calls for the development of internal combustion engine modeling logic. Task 3 develops hybridization logic or the sizing and synthesis modeling logic to account for the tight coupling between the electric/energy storage devices, mission analysis, and the fuel consuming engine.

Research Objectives: The research objectives are subdivided into three main tasks which are as follows:
- **Task 1** - Identification and Modelling of relevant hybrid-electric propulsion architectures and resulting system components of interest for vertical lift aircraft in the 3 to 1300 pound weight range.
- **Task 2** – Development of the modeling logic to perform on-design and off-design analysis for internal combustion engines. The modeling logic will be focused on sizing critical components and creation of logic to predict power characteristics and associated fuel flows.
- **Task 3** - Development of a sizing and synthesis modeling logic for hybridization of the overall system that involves consideration of the mission requirements, electrical elements and internal combustion engine.

Accomplishments: For task 1, a theory manual was created which documents the theory of the components required to analyze various types of hybrid-electric propulsion architectures. The theory provides equations that relate the geometry of the components with the torque and speed requirements of the air vehicle design and also the calculation of off-design performance. In this way, parametric scaling relationships of the components are detailed. For task 2, a NPSS model was created for the internal combustion engine. The internal combustion engine is modeled as a single element since most of the thermodynamic processes are occurring within the engine cylinder. The element was contained in a file in which performance calculations are carried out. The element inputs several parameters including engine speed, geometry, fuel properties, and burner efficiency. Each

stage of the engine cycle is represented by an NPSS Flow Station, which defines the thermodynamic properties of a flow. Task 3 involved synthesizing the various elements created in NPSS in order to create a hybrid electric system model and relevant documentation of the logic used. A conference paper entitled 'Modeling and Requirements Definition for a Hybrid-Electric Powered Helicopter' was also created and presented at the AHS Sustainability Conference 2015. The principal goals of this paper were the modeling of the components of a hybrid electric system and the assembly of the resulting system architecture. Secondly, the system level model developed was used to investigate the viability of a hybrid propulsion system on a helicopter similar to the Robinson R-22 aircraft. In addition to analyzing the current technology level, the requirements space for a hybrid electric helicopter was investigated and compared to both all-electric and piston engine only results in order to set technology targets for future development.

Students supported under the project
1. Jonathan Gladin (US): 100% time - PhD Completed December 2015
2. Manish Pokhrel (Nepal): 100% time – MS/PhD anticipated 2017/2020
3. Kegan Ali (US): 100% time – MS completed December 2015
4. Antoine Engerand (France): 3 months on project – MS completed December 2014

Patents/Software Invention Disclosures

Publications

Theses:

No details provided

Journal Papers:

No details provided

Conference Papers:

1. Manish Pokhrel, Jonathan Gladin, Kegan Ali, Kyle Collins, Dimitri N. Mavris, "Modeling and Requirements Definition for a Hybrid-Electric Powered Helicopter", in Proceedings of the 2015 American Helicopter Society Sustainability 2015 - International Conference on Environmental Sustainability in Air Vehicle Design and Operations of Helicopters and Airplanes, Montreal, QC, Canada, September 22-24, 2015

Awards
none

Technical Transfer

Task 1.13 (GT-21): Development and Demonstration of Methodologies for Ship-Airwake Simulations

PIs: Marilyn J. Smith (Georgia Tech)

Background: Operation of flight vehicles in the vicinity of naval ships is challenging due to the complex vortical structures shed from the bow of the ship and other ship structures, such as hangars, decks, turrets, cables, and parked air vehicles, for example. A helicopter trying to land on a ship deck aft of a hangar may have to descend through a shear layer and shed vortices emanating from the roof of the hangar.

Flight conditions are exacerbated by highly unsteady aerodynamics due to ambient turbulence and the motion of the sea. Turbulent fluctuations from the atmospheric boundary layer (ABL) modify the free-stream mean flow and are believed to have a significant effect on ship airwake behavior for some ship configurations. For small deck ships, the unsteady bluff wakes may be significantly greater than the ABL disturbances. This is also the case for large deck ships except that there is also a large rolled-up longitudinal vortex that emanates from the bow of the ship.

The need to better characterize this operating environment has motivated an international collaborative effort, from which a generic ship model known as the ``simple frigate shape'' (SFS) has been extensively studied.  A later iteration of this generic model, known as the ``simple frigate shape 2'' (SFS2), is a representative geometry of a ship topside to allow standardized study of ship topside aerodynamics with extensive available experimental data.

Previous ship-airwake numerical experiments applying unsteady Reynolds-averaged Navier-Stokes (URANS) solvers have noted errors in flow separation and reattachment locations, and even detached eddy simulation (DES) solvers encountered errors in the predicted turbulence intensity levels, and mean flow predictions under yawed flow conditions. While these URANS solvers have been successful, they require highly refined mesh spacing in areas of shed wakes from bluff bodies, significantly increasing computational cost potentially beyond the means of many engineering needs when rotorcraft and other flight operations are considered. An efficient, high-fidelity hybrid computational methodology combining a near-body URANS solver with an Eulerian vorticity-velocity approach has been shown to provide accurate wake predictions without the need for highly refined wake grids. Recent blind studies as a proof of concept indicated that this hybrid approach is also a candidate for ship-airwake simulations using data from the SFS2 Naval Surface Warfare Center Carderock Division (NSWCCD) wind tunnel tests.

Research Objectives: The research objectives for this two-year effort (at half time) include a) numerical evaluation of wind tunnel blockage and scaling effects to aid in developing databases behind complex structures such as ship wakes (Navy) and buildings (Army/NASA) and b) the development and demonstration of hybrid URANS approaches for complex separated physics associated with ship-airwakes.

Accomplishments: Using numerical experiments, computational fluid dynamics (CFD) has been used to assess the effect that wind tunnel blockage may have on the behavior of the near and far wake of the SFS2 ship model. These analysis is critical to inform both future experimental and computational efforts when large blockage and separation will be encountered. Correlations with extant wind tunnel data and new NSWCCD SFS2 data, have been used to assess the accuracy of the numerical experiments. The sensitivity of the simulations to downstream boundary conditions has been assessed and is planned to be formally reported at AVT and AIAA Aviation in 2018. Assessment included the unsteady velocity and unsteady flow features near the landing deck and farther aft in the flight path. The wake was modeled with large eddy simulation (LES) and detached eddy simulation (DES), which is currently state-of-the-art practice in CFD.

The influence that the model scaling has on the near and far wake of the SFS2 ship model has also be assessed; while the main features (shear layers, vortex shedding, recirculation) remain, the magnitude and direction of the local velocities has changed with the change in Reynolds number. This finding mirrors a conclusion for rotorcraft hub drag assessments in a prior ONR project that it is key to perform wind tunnel assessments above the critical Reynolds number of components such as cylinders which have different wakes at sub- and super-critical Reynolds numbers. The scaling effects are not linear for both fixed and Reynolds-number based separation configurations. For example, the vortex/separation/shear layer magnitudes and locations are not maintained from model to full scale. In particular, the separation/shear locations near the landing zone change, which can change pilot workload alleviation assessments based on model-scale wind tunnel tests.

Extension and evaluation of a hybrid finite-volume unsteady Reynolds-Averaged Navier-Stokes (URANS) with an Eulerian Vorticity Transport Method (VorTran-M) has also been evaluated to determine its capability in capturing these effects at much lower computational costs. This hybrid model is being compared with finite-volume solver results (FUN3D alone) to assess the accuracy and efficiency of the hybrid method. Focus of the accuracy assessment has been on the shed vorticity from the SFS2 model in the near and far wake, encompassing the area of a typical flight path by rotorcraft.

As there was a delay in receiving the data from NSWCC and the parallelized version of VTM, this task was suspended until late 2016 and 2017. The hybrid coupling approach with FUN3D has been completed. Using the same grids as in the blind studies, coupled with different fidelity background grids, simulations are being compared with existing data at 0° and 45° yaw angles. The parallelized FV/VTM capabilities are continuing assessment via a separate Department of Energy STTR with Continuum Dynamics, Inc. Two papers in 2018 (AVT and AIAA Aviation) will provide basic research guidance on best practices and influence of scale and blockage to enable 6.2-6.3 DoD future testing and database analysis in this area. Additional needs for accurate CFD validation and blockage approaches are discussed in these papers, which also leverage wind tunnel assessments in ARO and ONR basic research efforts. All

meshes, input decks, data for plotting will be made available to the Navy and other groups approved by the Navy.

Students supported under the project:
1. Philip Cross (USA): supported ~30% time in 2014-2016. currently pursuing PhD. This work will be part of his PhD thesis.
2. Eliot Quon (USA): products from PhD thesis developed/utilized in this work; not directly funded, awarded PhD 2014, Aerospace Engineer, NREL, CO.
3. Rajiv Shenoy (USA): products from PhD thesis developed/utilized in this work; not directly funded, awarded PhD 2014, Aerospace Engineer, Hampton, VA.

Patents/Software Invention Disclosures:

None at present.

Publications:

<u>Theses</u>

1. E. W. Quon. *Data Transfer Strategies for Overset and Hybrid Computational Methods*. PhD thesis, Georgia Institute of Technology, Atlanta, Georgia, 2014. https://smartech.gatech.edu/handle/1853/53024

2. R. Shenoy. *Overset Adaptive Strategies for Complex Rotating Systems*. PhD thesis, Georgia Institute of Technology, Atlanta, Georgia, 2014. https://smartech.gatech.edu/handle/1853/51796..

<u>Journal Papers</u>

1. E. Quon and M. J. Smith. Advanced Data Transfer Strategies for Overset Computational Methods. *Computers & Fluids*, 117:88–102, August 1 2015. doi:10.1016/j.compfluid.2015.04.023.

<u>Conference Papers:</u>
1. P. Cross, N. Rosenfeld, M. J. Smith. An Assessment of Blockage and Scaling on the Unsteady Aerodynamics of a Simplified Frigate Ship. Abstract under preparation for AIAA Aviation, Atlanta, GA, June 2018.
2. L. Jarman, P. Cross, A. Grubb, M. J. Smith. Large-Eddy-Simulation-Based Wind Tunnel Assessments. To be presented at the AVT, Torino Italy, April 2018.
3. E. Quon, M. J. Smith, P. Cross, N. Rosenfield, and G. Whitehouse. Investigation of Ship Airwakes Using a Hybrid Computational Methodology. Proceedings of the 70th American Helicopter Society Forum, Montreal, Canada, May 20–22 2014.
4. E. Quon, M. J. Smith, and G. Whitehouse. A Novel Computational Approach to Unsteady Aerodynamic and Aeroelastic Flow Simulation. Proceedings of the International Forum on Aeroelasticity and Structural Dynamics, Bristol, UK, June 2013.

Awards:

<u>Faculty Technical Awards:</u>

1. Marilyn Smith, Agusta-Westland International Fellowship Award (AHS, HART-II Workshop), 2012
2. Marilyn Smith, Agusta-Westland International Fellowship Award (AHS, US/France PA), 2014
3. Marilyn Smith, American Helicopter Society Technical Fellow, 2015
4. Marilyn Smith, AIAA Fellow, 2015
5. Marilyn Smith, NASA Group Achievement Award (FUN3D Development Team, rotorcraft contributions), 2017.
6. Marilyn Smith, Invited seminars at several places 2011-2017

<u>Student Technical Awards:</u>

1. Philip Cross, Georgia Tech Presidential Fellow, 2013-2016.
2. Philip Cross, Intern, AFDD, AMRDEC, Moffatt Field, CA, Summer 2016

Technology Transfer:

- This effort has involved collaborations with US Navy (Rosenfeld) for the SFS2 experimental data. The blockage efforts have resulted in an invitation to present at the NATO AVT 284 on boundary conditions for wind tunnel modeling.
- The hybrid methodology development has resulted in a Navy Phase I and Phase II STTR effort with Continuum Dynamics, Inc.

Task 1.14 (GT-22): Pasive Unmanned Aircraft Systems for Adaptive Sampling in a Riverine Environment

PI: Eric Johnson (Georgia Tech)

No writeup was provided in time for this draft report.

Task 1.15 (GT-23): A Pilot Cueing System for Helicopter Autorotation

PI: Jonathan Rogers (Georgia Tech)

Background: Task 23 was a 14-month effort to investigate novel pilot cueing methodologies for improving the safety and survivability of helicopter autorotation landings. The primary focus of the task was to develop a system for providing visual cues to pilots to recommend collective and longitudinal control inputs throughout the maneuver, from entry to landing. Such a system may potentially reduce workload by allowing the pilot to focus on identifying landing sites and maintaining vehicle stability. The cueing system developed here is driven by a fully-autonomous autorotation control law developed at Georgia Tech over the previous three years. During the course of this project, this control law was integrated into the University of Liverpool's HELIFLIGHT-R immersive simulation environment. A simple cockpit display was designed, driven by inputs from the autorotation control law, that recommends collective and longitudinal cyclic positions throughout the maneuver. A series of flight tests using this simulator have been performed, and more are scheduled to take place during the first several months of 2017. During these tests, pilots fly simulated autorotations with and without the pilot cueing system in degraded visual environments. Objective and subjective (pilot survey) data are used to evaluate the efficacy of the prototype cueing system. The outcomes and lessons learned from this exploratory project will inform the more extensive research program (Task 9) pursued as part of the 2016 VLRCOE.

Research Objectives: The primary objectives of this effort are focused on the development and implementation of a prototype pilot cueing system for use in autorotation. First, the autorotation control law previously developed by Georgia Tech was tuned for the UH-60 aircraft and integrated into the University of Liverpool HELIFLIGHT-R simulator. In parallel, a rudimentary cockpit display was designed to provide heads-up pilot cueing for the suggested collective and longitudinal cyclic stick positions. The cockpit display was driven by the autorotation control law. Finally, a series of flight tests were performed (and are currently underway) to evaluate the efficacy of the display for a nominal autorotation maneuver scenario. Objective and subjective data are used to evaluate performance of the flight display and suggest further improvements.

Accomplishments: The autorotation control law developed by Georgia Tech was originally created in C++ and needed to be rewritten in Simulink to facilitate integration with University of Liverpool's HELIFLIGHT-R simulator. During the first three months of the project, Georgia Tech implemented the full autorotation control law as a Simulink block diagram.

The example vehicle selected for this project was the UH-60, primarily because a set of input files for this aircraft is already available for the UoL simulator. As such, the autorotation control law was tuned for the UH-60 aircraft. This involved the tuning of about 7-8 different control parameters adjusting the flare trajectory, phase transitions, and pitch angle saturation limits. Initial tuning was conducted using Georgia Tech's helicopter simulation model, prior to sending the control law to UoL for integration.

The outcome of the tuning process at Georgia Tech was a control law that could autonomously land the UH-60 in autorotation. Given the suitable performance of the autorotation control law in the Georgia Tech simulator, UoL began the process of integrating the Simulink controller into the HELIFLIGHT-R environment. This process took place during the summer of 2016, and was completed around 1 September. The autorotation control law was configured to drive a cockpit display, with the controller outputs forming the recommended collective and longitudinal cyclic values provided to the pilot. It was verified that the controller could reliably run faster than real-time.
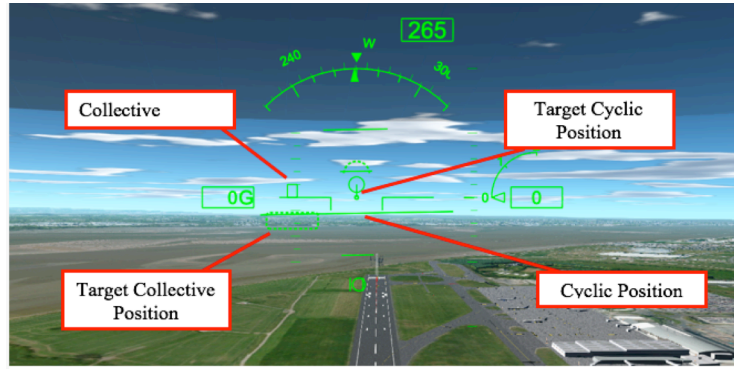

Fig 1. HELIFLIGHT-R Autorotation Cockpit Display.

During September-October 2016, a preliminary heads-up display was designed by UoL to provide the pilot with recommended control position information in autorotation. An image of this display is shown in Figure 1. It consists of the usual basic pilotage information, and also contains four additional symbols that provide autorotation cueing information to the pilot. Two symbols provide visual information as to the current actual longitudinal cyclic and collective positions while the other two symbols provide the desired cyclic and collective control positions (taken directly from the autorotation algorithm). The pilot's task is to overlay the desired and actual position for each control inceptor for each phase of the maneuver.

Model discrepancies between the HELIFLIGHT-R and Georgia Tech simulations necessitated additional tuning of the autorotation controller, which took place in January 2017. However, using only the entry and steady-state portions of the maneuver, preliminary piloted flight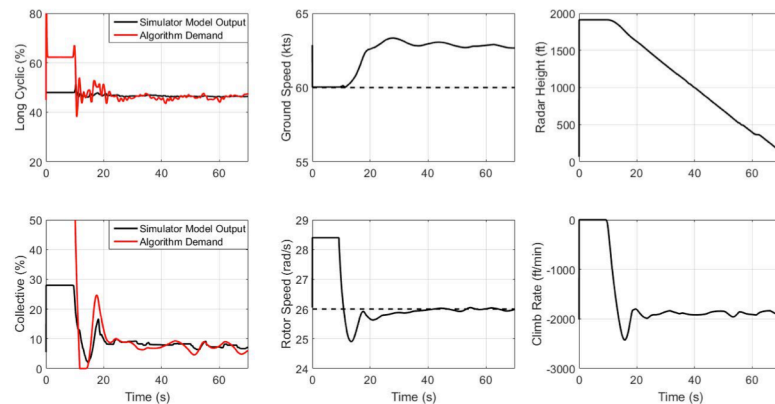 tests were undertaken limited to this phase only. Figure 2 shows an example entry into an autorotative descent flown in the University of Liverpool's HELIFLIGHT-R flight simulation facility where the engineer pilot was cued by the autorotation

Fig 3. Example Manual Steady-State Autorotation Cued by Algorithm

algorithm's outputs displayed on the HUD. The set-points are shown in this figure as dotted lines and the initial 10 seconds or so of data represent the trimmed flight condition prior to the engine failure being triggered. It can be seen that following an initial transient and an oscillatory response on the collective, the pilot is able to settle into a steady state descent at the required rotor speed and at a forward speed of around 63 knots. This resulted in a descent rate of around 1800 feet per minute which is considered to be acceptable for this phase of the maneuver.

As of January 2017, Georgia Tech and UoL are working to fine-tune the autorotation controller in preparation for more extensive flight testing. These experiments will be completed and evaluated by the end of February 2017.

Students supported under the project:

1. Laura Strickland: supported 10% time, 2016, PhD anticipated December 2018.
2. Jonathan Warner: supported 20% time, 2016, PhD anticipated December 2017.
3. Caroline Repola: supported 10% time, 2016, MS September 2017.

Patents/Software Invention Disclosures:

N/A

Publications:

Theses:

1. Repola, C., "Implementation and Tuning of an Extended Expert Control System for Helicopter Autorotation," MS Thesis, Georgia Institute of Technology, September 2017.

Journal Papers:

N/A

Conference Papers:

1. Strickland, J., Repola, C., Rogers, J., Jump, M., Cameron, N., Fell, T., "Handling Qualities Assessment of a Pilot Cueing System for Autorotation Maneuvers," 73rd AHS Annual Forum, Fort Worth, TX, May 9-11, 2017.

Awards:

Project Technical Awards:

N/A

Faculty Technical Awards

1. Jonathan Rogers, National Science Foundation CAREER Award, 2016
2. Jonathan Rogers, Lockheed Martin Inspirational Young Faculty Award, 2016

Student Technical Awards

N/A

Technical Transfer

N/A

Task 1.16 (GT-24): Numerical Rotorcraft Propulsion System Simulation of Compression Ignition Engines

PIs: Dimitri Mavris (Georgia Tech) and Jonathan Gladin (Georgia Tech)

Background: The U.S. Army Aviation Development Directorate Concept Design and Assessment (CD&A) Tech Area has the capability to model a variety of configurations, spanning the current fleet of rotorcraft and many of the experimental VTOL concepts. The tools used typically model the propulsion system in a reduced order form that reflects the performance and fuel consumption based on data from the manufacturer or higher fidelity modeling. In recent efforts to develop component models of hybrid-electric sub-systems, the Aerospace Systems Design Laboratory (ASDL) at the Georgia Institute of Technology built thermodynamic cycle models of an internal combustion engine with spark ignition. The work proposed for this task is meant to extend this modeling to various types of compression (diesel) ignition engines. Data obtained from these higher fidelity simulations of diesel engines can then be reduced to a form for use in a sizing and synthesis tool so that it can be included as a propulsion system in a rotary wing vehicle; whether alone or included as a component of a hybrid-electric system.

The motivation for modeling diesel engines is threefold. For one, there are a number of manufacturers who are offering diesel engines for general aviation aircraft. The availability of these engines and their continued development will make them applicable for smaller, training helicopter and UAVs. Second, the engines can be fueled by Jet-A, which is available – and usually cheaper – in more parts of the world than 100 LL. This makes the rotorcraft and UAVs using these types of power systems be more globally relevant. Third, the actual fuel consumption of diesels is better than similar power producing spark ignition models. For these reasons, being able to include diesel engines as a possible alternative propulsion system in the early phases of design during sizing and synthesis is a major motivator for the work shown in this document.

Research Objectives: Georgia Tech's Aerospace Systems Design Laboratory (ASDL) performs engine cycle analysis with Numerical Propulsion System Simulation (NPSS). Using NPSS allows for creation of a model that will provide parametric scaling capabilities including changes in weight, high level geometry, and performance. Current capability does not include modeling of a diesel engine cycle within the NPSS framework. This will be achieved by accomplishing the following research objectives:
- Model and validate the diesel (compression ignition) engine cycle. Focus will be on power plants in the 50 – 200 horsepower range.
- Model additional cycle enhancing components in NPSS to simulate turbo-charging and super-charging of the diesel engine. The basic diesel cycle model will be combined with the ancillary components to represent the augmented cycles.
- Cycle model validation will be performed for the diesel cycle, turbo-diesel, and a super-charged turbo-diesel. Model results will be validated against open-source data provided and approved by the sponsor.

Accomplishments: The NPSS programming language and thermodynamic packages were used to implement a basic diesel cycle model. Modifications to the existing internal combustion engine model were required to represent the diesel cycle. A literature search was performed to determine suitable methods for modeling the losses within the diesel engine at a conceptual level. An approach was selected that quantified each of the components of the engine loss based on their physical mechanism with a focus on representing the losses as a function of engine speed (RPM) and cylinder pressure to capture the operational space of a rotorcraft engine and variability in the specific fuel consumption. As a first step, a verification exercise was conducted to justify the selection of the approach. This exercise was conducted by referencing open source data sets for naturally aspirated engines – those without any supercharging of the intake. Initial studies using estimates for the engine loss showed that the overall cycle model predicted power levels very well given the displacement volume of the two engines that were selected for validation, but the specific fuel consumption trends did not properly reflect the data.

To address this challenge, a MATLAB calibration tool was created to determine the necessary level of loss at each operating range in the data set. The required FMEP (friction mean effective pressure) is determined at each point to properly fit the output power of the data set and this data is used to calibrate the loss model coefficients. The use of this approach resulted in a very tight fit for output power between the model results and the data set for the range of engine speeds applied. The overall level of the specific fuel consumption was reasonable as compared to the validation set, however, the trend with RPM did not match the data as well. As such, it was determined that the remaining variable to be matched at each of the engine speeds is the fuel-to-air ratio or mixture ratio of the engine.

For compression ignition engines, the mixture ratio can take on a wide value in the range of roughly 16:1 to 60:1. Furthermore, the throttle of a diesel engine controls the fuel to air ratio to vary the RPM of the engine, so the FAR needs to be calibrated at each operating condition to match the fuel flow rate of the data set. An approach was derived to calibrate the fuel flow at each point in the data set simultaneously with the power curve. An initial constant FAR is used to compute the power calibrated data set and the necessary change to the FAR at each RPM is calculated to match the BSFC between the model predicted value and the data. The resulting FAR vs. RPM curve is input into the NPSS model and final comparison runs are conducted. The MATLAB calibration was updated to contain a small GUI to allow the user to interactively change many of the other inputs to the model. The tool was streamlined to produce both output and graphical representation of the results from the calibration process. The tool was tested on two different engine data sets to further demonstrate the validity of the approach.

In task 2, "cycle enhancing" elements were developed in NPSS to allow the diesel engine model to be "upgraded" by increasing the charge pressure, density, and mass flow by compressing the intake. Two architecture diagrams were created to represent the components required to build a performance model

for the ancillary systems required to drive the engine supercharger. These architectures included a compressor, turbine, and intercooler system that are required to charge the intake as well as various intake ports and bleed valves that can change the flow through each of the components. Many of the components in this system were able to represented using basic models in the NPSS program standard set. The basic NPSS compressor and turbine elements were used, however, the losses and efficiency maps were created using open source tools that are available to model small centrifugal machines. The heat exchanger was modeled using a text book approach with code that was directly implemented in the NPSS model that predicts the effectiveness of the heat transfer for the intercooler. A sizing and control approach was developed to control the intercooled temperature by modulating the cold-side flow of the heat exchanger, which was supplied with ram air. Much effort was expended to achieve convergence for the IC engine and the supercharger sub-system as a whole and this was achieved over a large variety of operating conditions for the sample test case.

The final task was to use the NPSS environment to represent the performance of the continental high altitude centurion diesel engine (CD-155). The architecture is a turbo-diesel engine and the model was set up to reflect that physical setup. The data for RPM and horsepower output were provided by the sponsor at various combinations of altitude and RPM and served as a validation set for this process. For the supercharger system, it was necessary to determine the proper sizing point and operating schedule for the compressor and turbine. This was determined through several design iterations between the model output and the data set. Finally, a sizing procedure for the subsystem design variables was determined to be appropriate for this problem. The only remaining task was to determine the required mass flow schedule for the turbocharger system. This can be controlled by varying the "waste gate" valve in the model to control the power output of the turbo. This schedule was manipulated to calibrate the power output at high altitude. This calibration procedure was combined with the prior procedure developed for the naturally aspirated engines to calibrate to the entire Centurion data set. Final results match very well with the data set at all altitudes and at sea-level performance. The calibration process was integrated into the MATLAB tool and additional user input variables were created for the graphical user interface.

Students supported under the project
1. Konstantinos Milios: supported 100% time, 2016-2017, candidate for M.S. in 2018
2. Mingxuan Shi: supported 100% time beginning April 2017, PhD anticipated 2019/2020

Patents/Software Invention Disclosures

Publications

Theses:

Journal Papers:

Conference Papers:

1. Mingxuan Shi, Konstantinos Milios, Jonathan Gladin, Dimitri N. Mavris, "System-level Study of Different Super/Turbocharger Architectures for Rotorcraft Diesel Engine", to be presented at the 2018 AIAA Sci Tech conference, Orlando Fl.

Awards

Technical Transfer

Task 1.17 (GT-25): Reduced Order Linear Time Invariant Models and Algorithms for Integrated Flight and Rotor Control

PIs: Peretz P. Friedmann (UM)

Background: Vibration reduction in rotorcraft using active control has been a major area of research for over four decades. Vibration reduction is a major objective in the design of modern rotorcraft. The Sikorsky Raider, under development, as well as the X2 Technology Demonstrator (X2TD), the coaxial rotors employ very stiff composite blades in flap, lead-lag, and torsion. Such configurations produce high vibration levels that may require active vibration control. On-blade active control (OBC) approaches, such as the actively controlled plain trailing-edge flaps (ACF) have been shown to be effective for rotorcraft vibration reduction. However, the interaction of OBC implemented by active flaps with the helicopter flight control systems (HFC) and its handling qualities is not well understood. Understanding the interaction between high-bandwidth control employed by OBC systems and the closed-loop flight control systems is a pre-requisite to OBC implementation on a production helicopter.

The handling qualities specifications for small amplitude maneuvers are based on linear time-invariant (LTI) models. Furthermore, LTI models provide a convenient framework for control system design. Thus, extraction of a LTI approximation of the helicopter dynamics is an essential step towards carrying out OBC and HFC interaction studies. During the first four years under Task 12 methods to extract LTI models from nonlinear periodic models using the Fourier expansion based model reduction (FEMR) were developed. The LTI models extracted at the University of Michigan are based on the AVINOR (Active VIbration and Noise Reduction) code, which is a high fidelity nonlinear helicopter aeroelastic analysis code that accounts for on-blade control implemented by flap or microflaps. It was found that the LTI models can represent the fully nonlinear model quite well, however, the fidelity of the LTI model is strongly dependent on the incorporation of the unsteady aerodynamic states. The AVINOR code uses a computational fluid dynamics (CFD) based rational function approximation (RFA) aerodynamic state-space model that can accurately capture the unsteady aerodynamics of the blade/flap combination when the flaps are operated at the high frequencies as is required for vibration reduction. Inclusion of the states associated with the RFA model reduced the error in the peak-to-peak hub load amplitude predictions from over 80% to under 10%.

An accurate computational simulation of an OBC based vibration reduction system and its interaction with the HFC system requires several components such as: (a) a coupled rotor-fuselage model, (b) a high-fidelity aerodynamic model capable of simulating OBC devices operating at high frequencies, (c) a free wake model combined with semi-empirical dynamic stall models for generating accurate vibratory hub shears and moments, (d) a closed-loop control algorithm that includes saturation limits, and (e) a robust linearization methodology combined with FEMR to extract the LTI models. The AVINOR code developed at the University of Michigan contains all these components except one – *a coupled rotor/fuselage model that can be used to model a maneuvering helicopter*. Adding the coupled rotor/fuselage model to AVINOR would be a time

consuming task and the resulting code will be of limited value, because the modified code would still be a university research code.

Research Objectives: As an alternative to AVINOR code, the Rotorcraft Comprehensive Analysis System (RCAS) code has been used in this project. The RCAS code has a robust and effective structural dynamic model, a coupled rotor/fuselage dynamic model suitable for modeling a maneuvering helicopter, and other aerodynamic modeling features such as a free wake model. However, the code lacks a high-fidelity state-space unsteady aerodynamic model capable of modeling high frequency blade and flap oscillations. Therefore, as part of this project, the CFD based RFA aerodynamic model, which is currently a part of the AVINOR code, was incorporated in to RCAS. The enhanced RCAS code is also validated against flight tests and results from Helios (Helicopter Overset Simulations) based full-scale CFD simulations. The RCAS code is used for a variety of applications by government agencies and industry, thus, making enhancements to it has important benefits.

Accomplishments: The CFD based RFA aerodynamic model was combined with the RCAS code using an available communication protocol for external components. This feature is available only on the LINUX (CENTOS) version of RCAS. The external aerodynamic component is comprised of a Fortran (.f) file and a component definition (.cdf) file. The Fortran file consists of subroutines which are invoked within the RCAS source code at various stages of the simulation. The .cdf file consists of declarations of variables and subroutines used in the Fortran file.

The UH-60A rotor model was used to validate the CFD/RFA model embedded in to the RCAS code. Simulations were performed for the high-speed flight condition $\mu=0.37$, $C_T/\sigma=0.081$, also referred to as the C8534 flight test case. This flight condition is characterized by compressibility, negative lift, and large aerodynamic pitching moment on the advancing side. Several studies have compared flight test data for the C8534 test case against coupled CSD/CFD coupled analysis results obtained using RCAS for structural modeling and the Helios environment for aerodynamic modeling. Structural load predictions from the RCAS and CFD/RFA combination are compared against the RCAS/Helios predictions and the flight test measurements in Fig. 1. Also shown in the figure are predictions from RCAS and a quasi-steady aerodynamic model combination. The flap bending moment and chord bending moment at 50%R are shown in Figs. 1(a) and 1(b), respectively. It is important to note that the RCAS/RFA aerodynamic model prediction (shown in solid green line) is as good as the RCAS/Helios prediction in both flap and chord bending moments. At certain azimuth angles, the flap bending moment between 200° and 250° and chord bending moment between 200° and 360°, the RCAS/RFA model shows better agreement compared to the RCAS/Helios predictions. At other azimuth angles the RCAS/Helios code shows better agreement with the flight data. The level of accuracy obtained from RCAS/RFA is very good considering that the computational time required is two or three orders of magnitude less compared to the RCAS/Helios code.

The torsional moment prediction obtained from CFD/RFA model at 70%R location, shown in Fig. 1(c), does not agree well with the flight test measurements. The reason for this is that the CFD/RFA model used in this study is based on CFD data for a NACA0012 airfoil. The RCAS/Helios simulations are based on the SC1095 airfoil which is also the airfoil used on the UH-60A blade. The SC1095 is a cambered airfoil and it differs from the symmetric NACA0012 primarily in pitching moment. Reconstructing the CFD/RFA model using CFD data for a SC1095 will most likely improve the torsional moment predictions as well as the flap and chord bending moments. The CFD/RFA model, due to its accuracy and computational efficiency, is an excellent alternative to the high-fidelity CFD codes used in Helios. The accuracy of the CFD/RFA predictions are comparable to the full-scale CFD simulations whereas the computational time required is comparable to the traditional quasi-steady models. It is conducive to both open-loop and closed-loop control as well as parametric trend studies, which can be formidably expensive if performed using a full-scale CFD setup. The CFD/RFA model is expressed in the state-space form and therefore lends itself naturally to linearized time-invariant (LTI) model extraction.

Students supported under the project:

1. Ashwani Padthe, Research Investigator, University of Michigan.

Patents/Software Invention Disclosures:
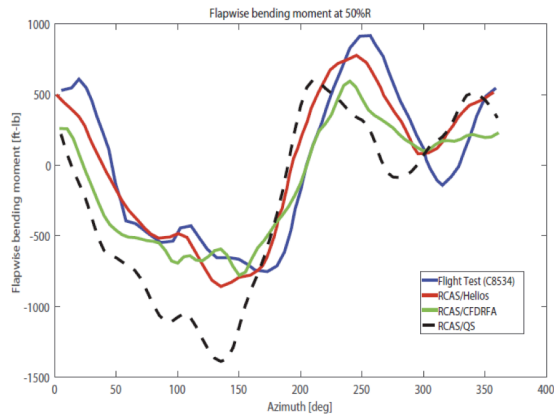
Publications:
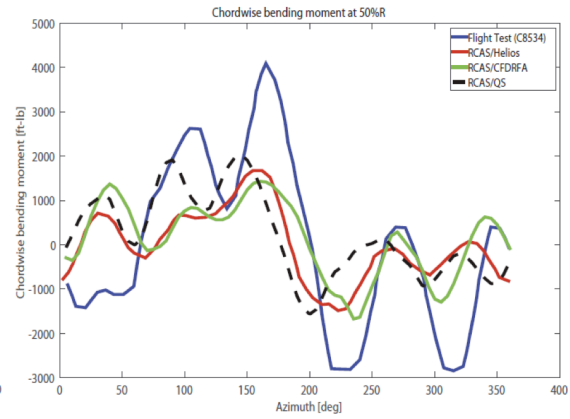
None to report

Awards:
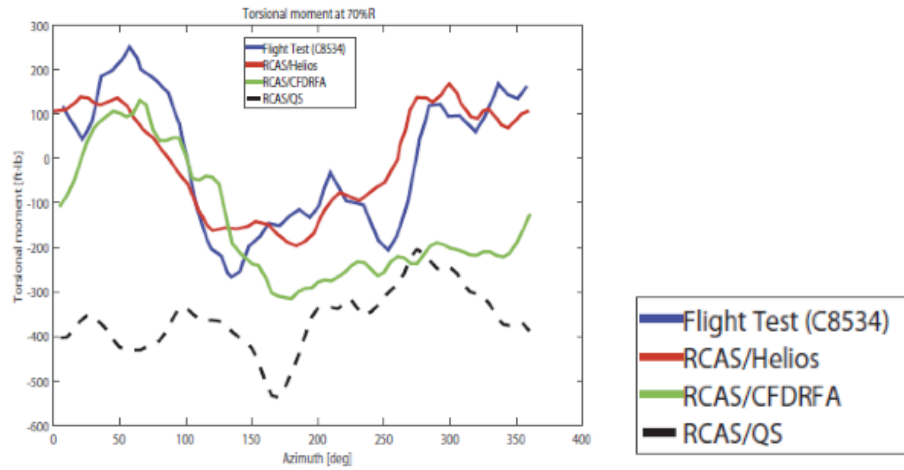
None to report

Technology Transfer:

Modifications to RCAS that will be available to all users.

(a) Flapwise Bending Moment at 50%R

(b) Chordwise Bending Moment at 50%R

(c) Torsional Moment at

Fig. 1: Comparison of predicted and measured structural load time histories for a UH-60A rotor at μ=0.37, C_T/σ=0.081 (C8534)